Systems Integration and Analysis Technical Area Overview

Winter Program Review – March 3 – 4th, 2022

Alex Huning, Oak Ridge National Laboratory
Technical Area Lead

Agenda for this session

10:25 Overview	**Alex Huning**
10:40 Global Market Analysis	David Shropshire
11:10 Regulatory Support for Microreactors	Jason Christensen
11:40 NEUP – MIT, Flex. Siting. and Staff…	Jacopo Buongiorno
12:00 NEUP – UI, MR req. and micro-grid…	Caleb Brooks
12:20 – 12:35, Wrap up	Alex Huning

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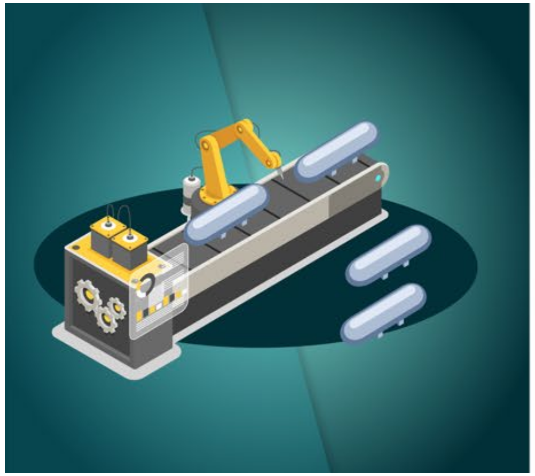
Scope (Microreactor program plan, INL/EXT-20-58919)

- **Systems Integration & Analysis** – This scope will identify the needs, applications and functional requirements for microreactors through **market analysis** which will be used to drive future focus of the Microreactor Program toward **improving economics and/or viability of microreactors**. It will seek understanding of the microreactor design space by investigating innovative microreactor technology supporting concepts and will **perform regulatory research** to help develop the regulatory basis for microreactor deployments.

Microreactor Key Features



Factor Fabricated

Transportable

Self-Regulating

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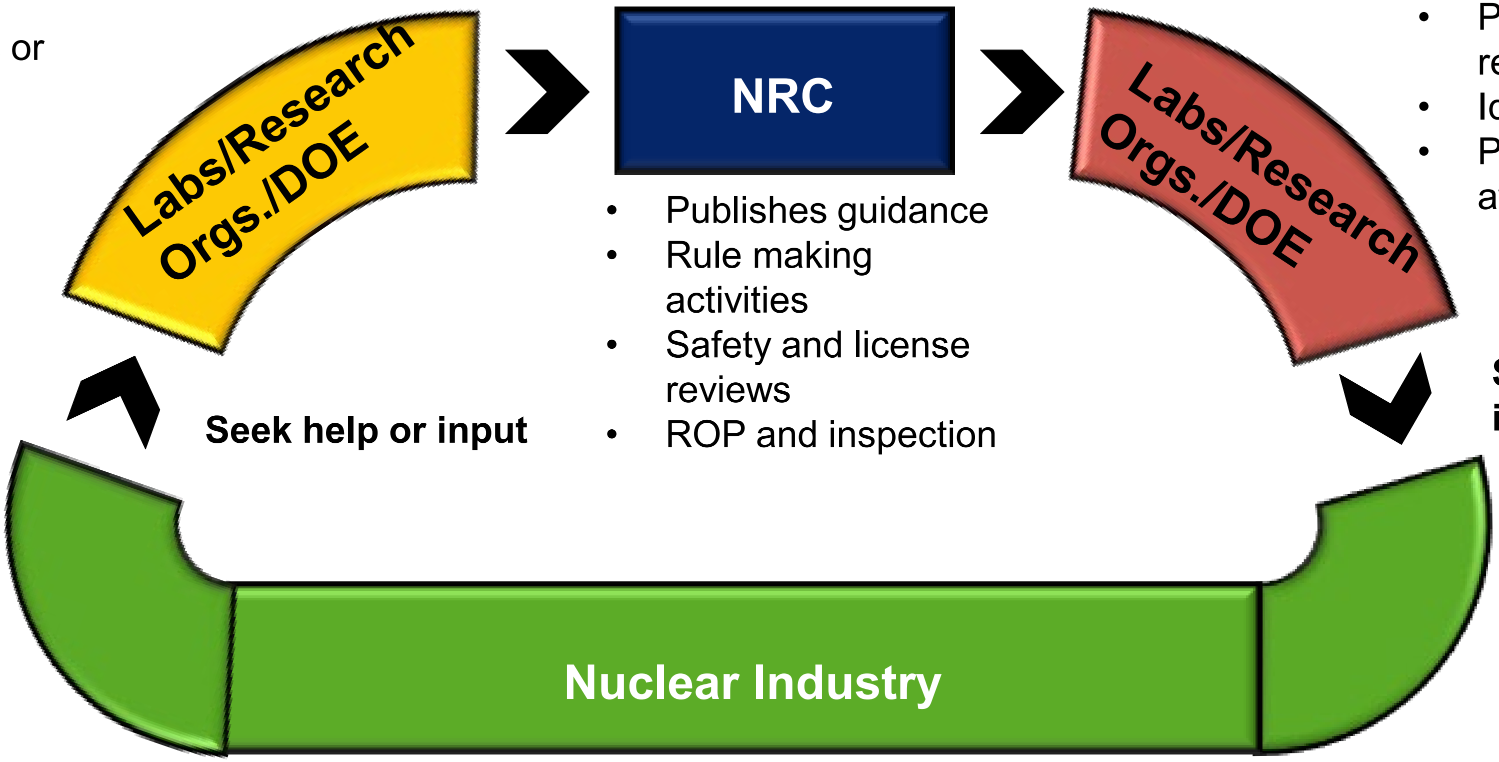
What role do research organizations have in nuclear regulations and licensing?



Informs the regulator

Guidance and regulations

Seek help or input

Supports implementation

Labs/Research Orgs./DOE

- Develops options for improving regulations or guidance
- Preforms analyses
- Collects data
- Supports codes and standards orgs.

NRC

- Publishes guidance
- Rule making activities
- Safety and license reviews
- ROP and inspection

Labs/Research Orgs./DOE

- Performs review of new guidance and regulations
- Provide feedback for regulatory improvement
- Identify broad issues
- Provide training and awareness to industry

Nuclear Industry

- Develops new technologies and/or applications pending regulatory approval
- Identifies specific regulatory challenges with existing fleet or associated with new reactor licensing and/or safety reviews

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How does the NRC view micro-reactor licensing?

Ref. NRC "Micro-reactor Licensing Strategies" (ML21328A189)

- *"NRC staff is receptive to requests for exemptions from the existing regulations"*
  - Caution: in practice this could be difficult and costly without additional guidance and agreement by the staff (see the quick note at the bottom)
- The NRC staff anticipates that:
  - **Reactor designs will be standardized**
  - **Manufactured and transported to a site with/without fuel**
  - Operational programs will be standardized
  - No site-specific departures (in the license and safety analysis) are anticipated
  - No spent fuel storage at the installation site
  - Generic EIS will be used
  - All ACRS and mandatory hearings will be conducted according to the AEA

Quick Note:

> In January of 2022, the NRC rejected Oklo's license application, without prejudice (i.e., they may reapply after a specified time)

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Design standardization observations

- No site-specific features relied on for safety
- Using bounding site parameters
- Operational programs are reviewed in the design stage:
  - Inservice inspection and testing
  - Environmental qualification
  - Reactor vessel material surveillance
  - Containment leak rate testing
  - Fire protection
  - Reactor operator training and qualification
  - Emergency planning
  - Security (cyber and physical)
- Final technical specifications are expected to be approved in a design certification for "group 1" programs (everything except for EP and security)

Challenge:

Heavy burden for industry and design organizations (especially "lean" organizations such as microreactors developers)

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Manufacturing license observations

- Reactors will be **(1) manufactured** and **(2) transported** along routes to **(3) sites** which all fall within site parameters postulated for the design
  - Proposed inspections, tests, analyses, and acceptance criteria needed for all three
  - Technical specifications
- ML license holders can only transport the produced reactors to sites which hold a construction permit or COL
- To install and operate the reactor an operating license or COL is needed
- No-fuel loaded reactors would reduce the need for site-specific inspections and verifications
  - This is then a trade-off with the design benefits of factory fueling
- Regulations for factory fueling are being developed and considered
  - A lot of transportation of SNM regulations
    - Specific exemptions likely
    - Our task is looking at regulation changes, suggestions

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Focus areas for FY21 and FY22

FY21 – Regulatory Research Planning for Microreactor Development

1-61847
evision 1

Regulatory Research Planning for Microreactor Development

July 2021

Jason Christensen
Idaho National Laboratory

Willis Poore
Oak Ridge National Laboratory

Randy Belles
Oak Ridge National Laboratory

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

Industry survey identified areas:

- Autonomous and Remote Control/Monitoring
- Grid Interaction
- **Factory Assembly**
- **Transportation**
- Staffing
- Digital Controls
- Instrumentation
- Modeling and Simulation
- Siting and Environmental Impact
- Security and Safeguards

FY22 – Regulatory Analysis of the Transportation of a Factory Manufactured Microreactor

Provide a background and gap analysis of the current transportation regulations for the transport of a microreactor from a factory-setting to a licensed site. Provide recommendations for the development of regulations to address the identified gaps.

+ 10 CFR Part 53 Developments and Implications

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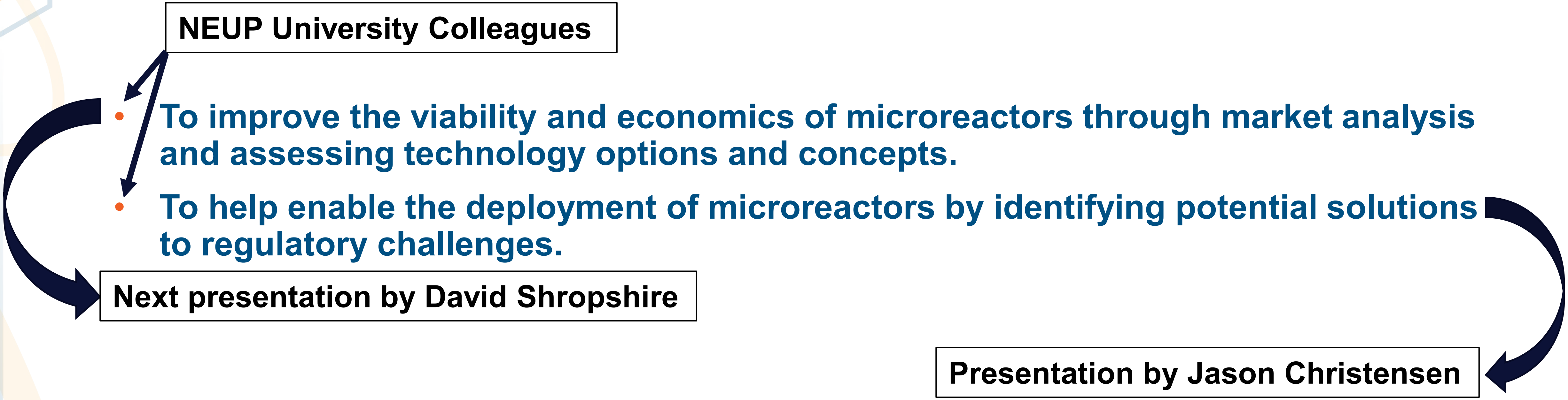
Execution of scope and SIA objectives



NEUP University Colleagues

- To improve the viability and economics of microreactors through market analysis and assessing technology options and concepts.
- To help enable the deployment of microreactors by identifying potential solutions to regulatory challenges.

Next presentation by David Shropshire

Presentation by Jason Christensen

Finally, in the wrap-up session…

How well is this executed, and how can we improve?

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Wrap-up discussion and questions?

Questions/comments?

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DOE-NE Microreactor Program

Global Market Analysis of Microreactors

David Shropshire | Idaho National Laboratory

Winter Review Meeting, March 3 - 4, 2022

Global Market Analysis of Microreactors (INL/EXT-21-63214)

World Nuclear News (WNN), 22 July 2021

- The report, Global Market Analysis of Microreactors, focuses on future global microreactor markets and the potential for microreactors, assessing their unique capabilities and potential deployment in specific global markets in the 2030-2050 timeframe.
- The 147-page study summarizes work on the economics and market opportunities for microreactors conducted under the DOE's Microreactor Program.
- It uses "top-down" and "bottom-up" analysis techniques to evaluate emerging market trends, derive a range of possible demands and rank potential markets in 63 countries including current nuclear energy users and so-called newcomer countries.

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Challenges and Opportunities (WNN) 1 of 2

"Results indicate significant potential for global deployment of microreactors, but also significant challenges in achieving the technical capacities, meeting regulatory requirements and international accords, achieving competitive costs and for gaining public acceptance," the report finds. Future market demand is seen to be particularly strong across Asia and Eastern Europe "in isolated operations and distributed energy applications".

Build rates in the hundreds of units by 2040 and in the thousands by 2050 would be needed to attain market penetration at scale and to fill "gaps" in the replacement of fossil sources for both electric and non-electric uses, as well as complementing variable renewable technologies such as solar and wind in distributed systems, the report says.

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Challenges and Opportunities (WNN) 2 of 2

"In basic market terms, for microreactors to achieve deep penetration in markets will require achieving specific aggressive cost targets; however, they will not compete with centralised energy sources," the report notes. "Consideration of costs beyond the demonstration units is necessary to insure producibility and scalability for factory deployment."

"For microreactors to capture new market shares, some significant challenges must be overcome, and an appropriate balance achieved between market demands, technology performance, costs, regulatory compliance costs and public acceptance," the report concludes. It notes that the "novelty aspects" of microreactors, competition for one or more dominant designs, and limited operational data "translate to uncertainty in the regulatory and planning domain".

Microreactor Specific and Benchmarking Indicators were identified

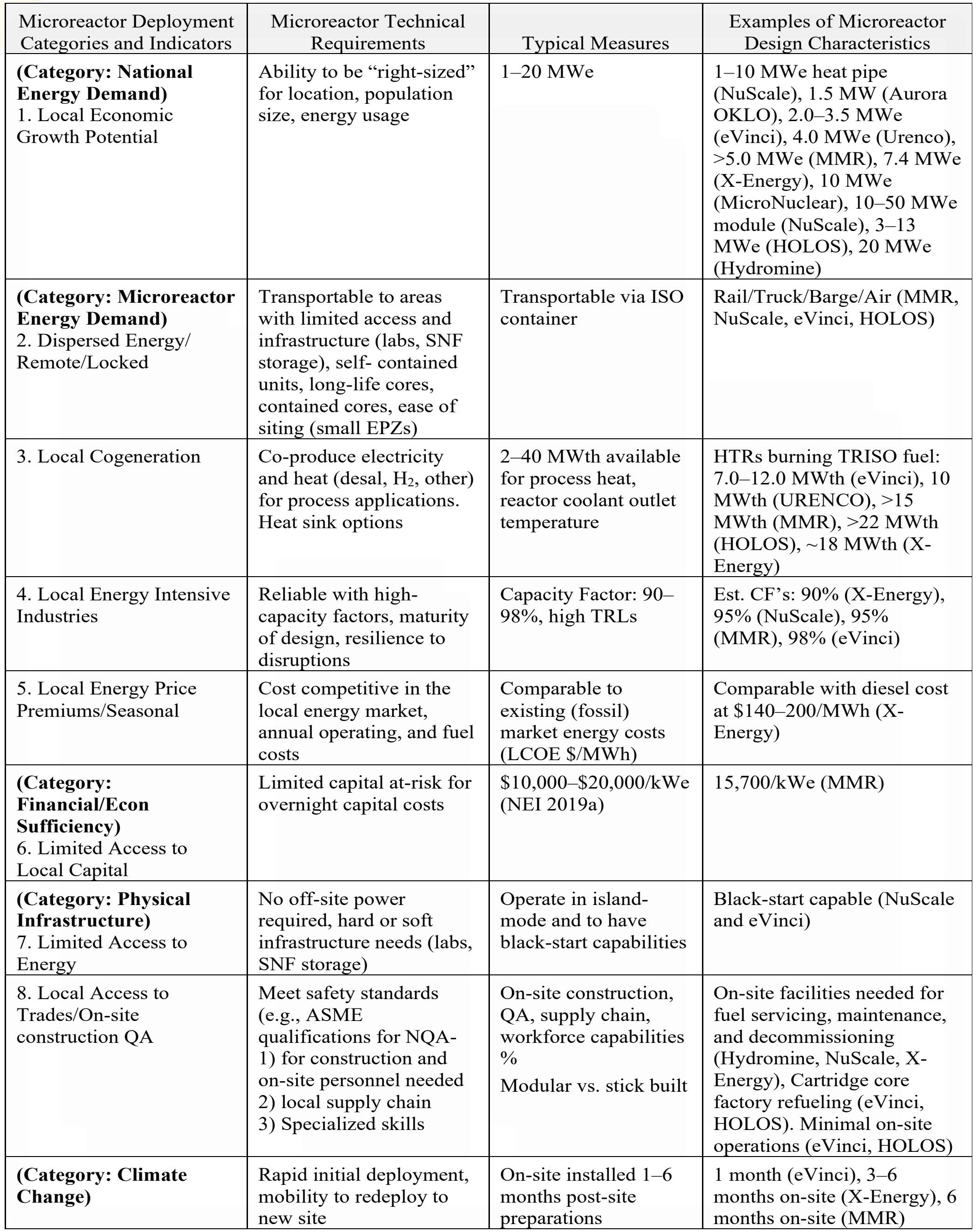
Microreactor Deployment Indicator Categories					
National Energy Demand	Microreactor Energy Demand	Financial/ Economic Sufficiency	Physical Infrastructure Sufficiency	Climate Change Motivation	Energy Supply Surety Motivation
🟨 Growth of economic activity (GDP GWTH)	🟩 Dispersed energy/remote/ land/locked (DISP/R/L)	🟨 Ability to support new investments (GDP/PC-GDP)	⬜ Electric grid capacity (GRID)	🟨 Reduce CO_2 emissions per capita (CO_2)	🟩 Reduce energy imports/ diversify energy sources (ENG IMP/DIV)
🟨 Growth rate of primary energy consumption (GRPEC)	🟩 Local cogeneration (LOC COGEN)	🟨 Openness to international trade (FDI/TRADE)	🟩 Limited access to energy (LAE)	🟨 Reduce fossil fuel energy consumption (FOSSFUEL/ OGC)	⬜ Use domestic uranium resources (URAN)
🟨 Per-capita energy consumption (PC-EC)	🟩 Local energy intensive industries (LEII)	🟨 Fitness for investment (CREDIT)	⬜ Land availability (LAND)	🟨 Achieve carbon reduction goals (NDC)	🟩 Balance intermittent renewables/ scalability (RES/SCALE)
🟩 Local economic growth potential (LEGP)	🟩 Local energy price premiums/ seasonal (LEPP/S)	🟩 Limited access to local capital (LOCCAP)	🟩 Limited access to trades/QA (TRADES/QA)	🟩 Local climate change/disaster vulnerability (LCC/DV)	🟩 Local critical loads/facilities (CRIT)

🟩 *Microreactor-specific indicator*	🟨 *Microreactor benchmarking indicator*	⬜ *Not applicable to microreactors*

Profile Markets were derived from microreactor use cases

Profile Market	Use Cases
Isolated Operations	Remote Mining Operations Military Installations Federal Facilities, critical loads University Campuses, critical loads
Distributed Energy	Small Rural Community Rural Hub Community Islands
Resilient Urban Applications	Regional Utility (e.g., Alaska Railbelt) Megacities
Marine Propulsion	Marine Propulsion
Disaster Relief	Disaster Relief

Indicators are translated into microreactor design characteristics



Microreactor Deployment Categories and Indicators	Microreactor Technical Requirements	Typical Measures	Examples of Microreactor Design Characteristics
(Category: National Energy Demand) 1. Local Economic Growth Potential	Ability to be “right-sized” for location, population size, energy usage	1–20 MWe	1–10 MWe heat pipe (NuScale), 1.5 MW (Aurora OKLO), 2.0–3.5 MWe (eVinci), 4.0 MWe (Urenco), >5.0 MWe (MMR), 7.4 MWe (X-Energy), 10 MWe (MicroNuclear), 10–50 MWe module (NuScale), 3–13 MWe (HOLOS), 20 MWe (Hydromine)
(Category: Microreactor Energy Demand) 2. Dispersed Energy/ Remote/Locked	Transportable to areas with limited access and infrastructure (labs, SNF storage), self- contained units, long-life cores, contained cores, ease of siting (small EPZs)	Transportable via ISO container	Rail/Truck/Barge/Air (MMR, NuScale, eVinci, HOLOS)
3. Local Cogeneration	Co-produce electricity and heat (desal, H_2, other) for process applications. Heat sink options	2–40 MWth available for process heat, reactor coolant outlet temperature	HTRs burning TRISO fuel: 7.0–12.0 MWth (eVinci), 10 MWth (URENCO), >15 MWth (MMR), >22 MWth (HOLOS), ~18 MWth (X-Energy)
4. Local Energy Intensive Industries	Reliable with high-capacity factors, maturity of design, resilience to disruptions	Capacity Factor: 90–98%, high TRLs	Est. CF’s: 90% (X-Energy), 95% (NuScale), 95% (MMR), 98% (eVinci)
5. Local Energy Price Premiums/Seasonal	Cost competitive in the local energy market, annual operating, and fuel costs	Comparable to existing (fossil) market energy costs (LCOE $/MWh)	Comparable with diesel cost at $140–200/MWh (X-Energy)
(Category: Financial/Econ Sufficiency) 6. Limited Access to Local Capital	Limited capital at-risk for overnight capital costs	$10,000–$20,000/kWe (NEI 2019a)	15,700/kWe (MMR)
(Category: Physical Infrastructure) 7. Limited Access to Energy	No off-site power required, hard or soft infrastructure needs (labs, SNF storage)	Operate in island-mode and to have black-start capabilities	Black-start capable (NuScale and eVinci)
8. Local Access to Trades/On-site construction QA	Meet safety standards (e.g., ASME qualifications for NQA-1) for construction and on-site personnel needed 2) local supply chain 3) Specialized skills	On-site construction, QA, supply chain, workforce capabilities % Modular vs. stick built	On-site facilities needed for fuel servicing, maintenance, and decommissioning (Hydromine, NuScale, X-Energy), Cartridge core factory refueling (eVinci, HOLOS). Minimal on-site operations (eVinci, HOLOS)
(Category: Climate Change)	Rapid initial deployment, mobility to redeploy to new site	On-site installed 1–6 months post-site preparations	1 month (eVinci), 3–6 months on-site (X-Energy), 6 months on-site (MMR)

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Microreactor
Market Economics

- Costs are initially high but can be competitive in remote operations (e.g., mining and defense).
- Use is expanded in distributed electricity markets when integrated in microgrids with other low-carbon energy systems.
- Market acceptance and continued cost reduction leads to adoption in urban/light industry as part of embedded energy systems.

Timeframe		**Cost Targets at Cumulative Number of Builds**				
1st Units	**Profile Markets**	**1-9**	**10**	**100**	**1,000**	**10,000**
2020-2030	FOAK units/ DoD Units	<$0.60/kWh				
2030-2035	Remote Operations		<$0.50/kWh	<$0.35/kWh	<$0.20/kWh	<$0.15/kWh
2035-2040	Distributed Energy			<$0.35/kWh	<$0.20/kWh	<$0.15/kWh
2040-2050	Resilient Cities				<$0.20/kWh	<$0.15/kWh

- Degree of market penetration is contingent on the ability to achieve low capital and operating costs, long refueling cycles, minimal infrastructure, and importantly - social acceptance.

- Economic potential may be increased through plug-in applications that create local economic growth (versus just replacement power).

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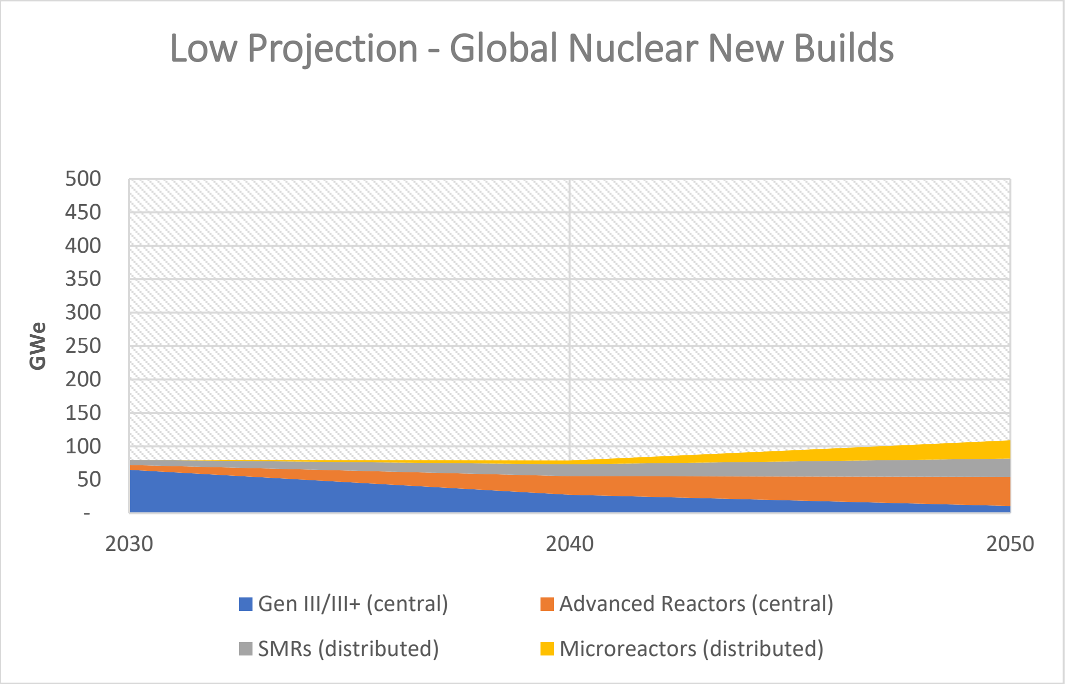
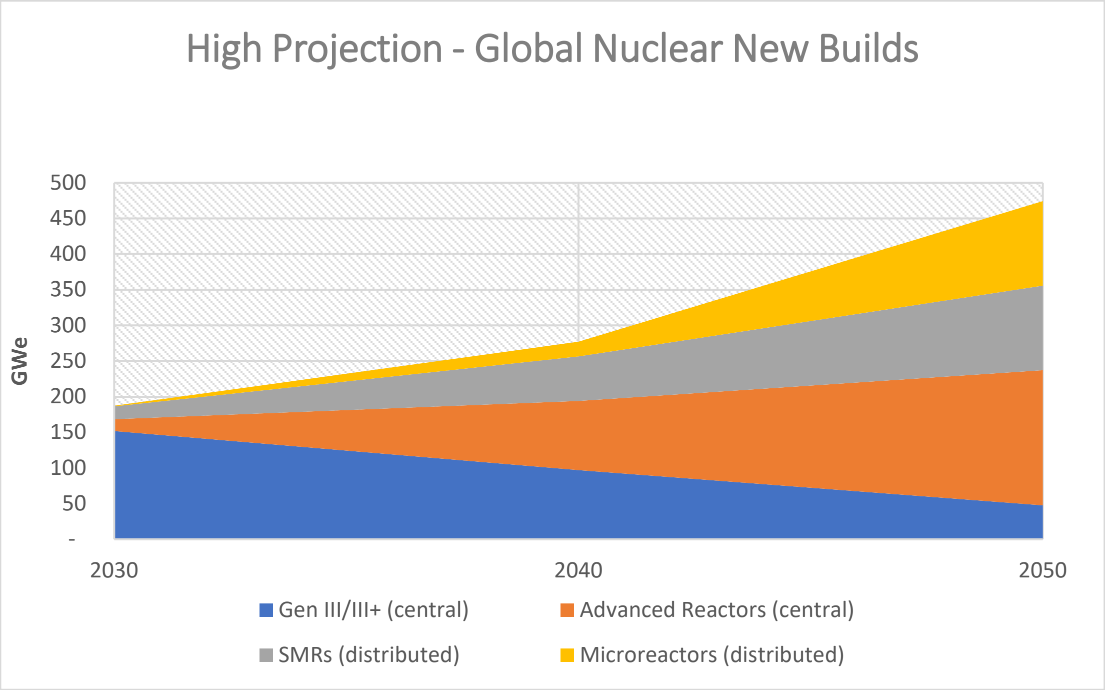
Microreactors were carved out of Global Nuclear Projections





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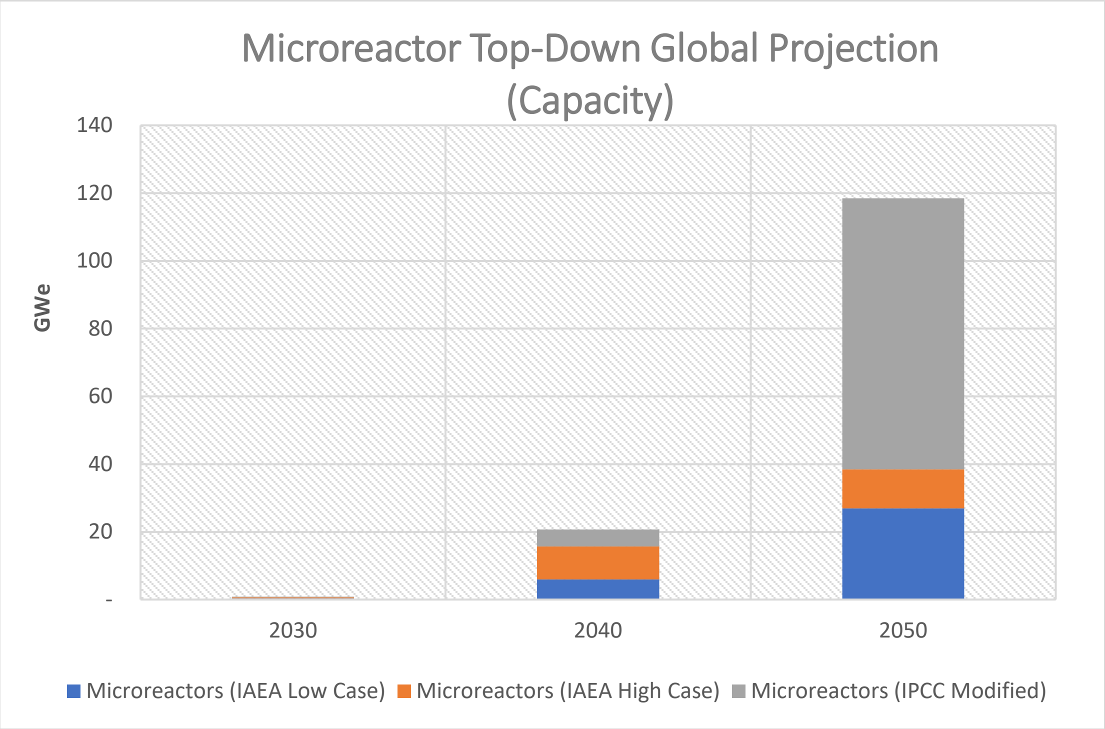
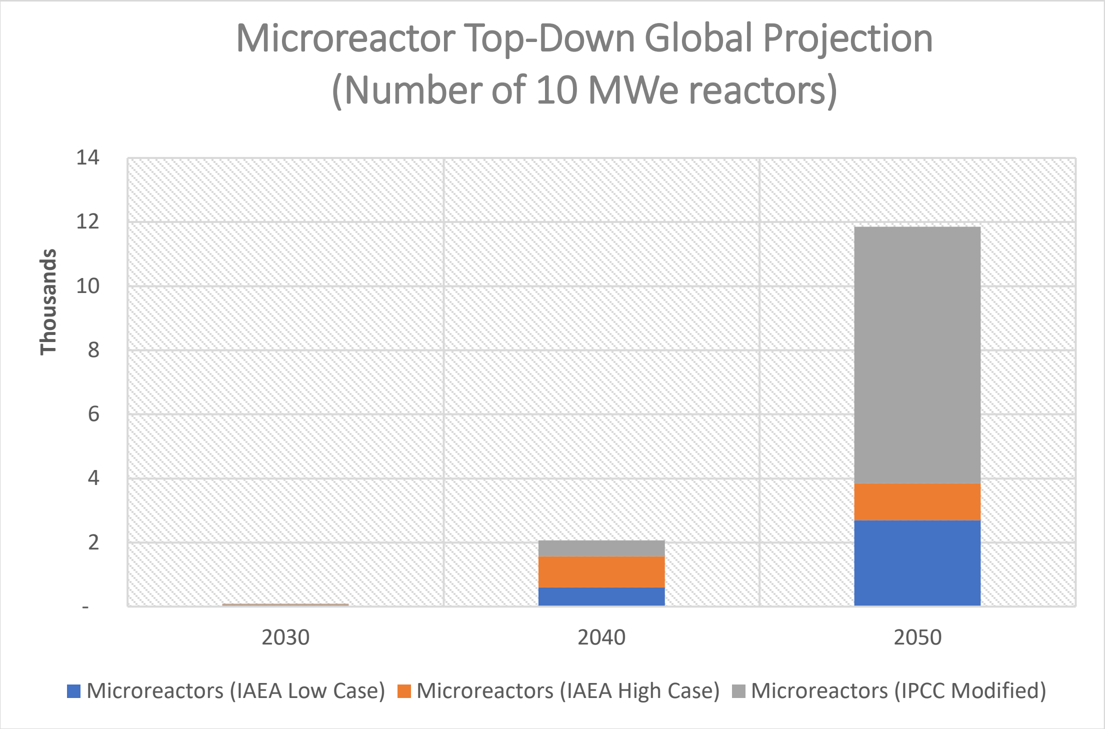
Microreactor Top-Down Global Projections





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Bottom-up Assessment covered 10 UN Regions including 63 nuclear power and emerging nuclear countries

Northern America	Latin America and the Caribbean	Northern, Western, and Southern Europe	Africa	Oceana
Canada	Argentina	Belgium	Algeria	
United States	Bolivia	Croatia	Egypt	
	Brazil	Finland	Ghana	
	Chile	France	Kenya	
	Cuba	Netherlands	Morocco	
	Ecuador	Slovenia	Namibia	
	Mexico	Spain	Niger	
	Paraguay	Sweden	Nigeria	
	Venezuela	United Kingdom	Sudan	
			South Africa	
			Tunisia	
			Uganda	

Eastern Europe	Western Asia	Southern Asia	Central and Eastern Asia	South-Eastern Asia
Belarus	Armenia	Bangladesh	China	Indonesia
Bulgaria	Azerbaijan	India	Japan	Laos
Czech Republic	Jordan	Iran	Korea	Philippines
Hungary	Saudi Arabia	Pakistan	Mongolia	Thailand
Poland	Turkey	Sri Lanka	Tajikistan	
Romania	United Arab Emirates		Uzbekistan	
Russian Federation	Yemen			
Slovakia				
Ukraine				

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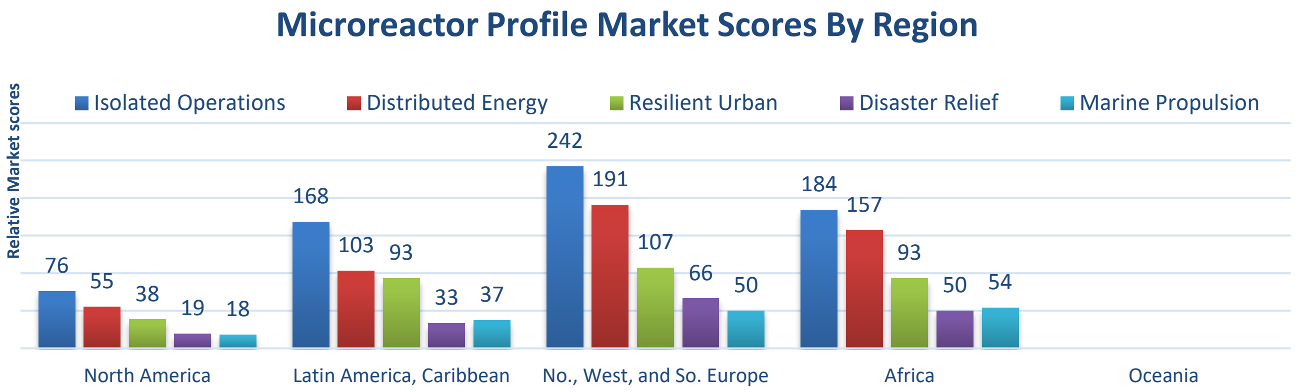
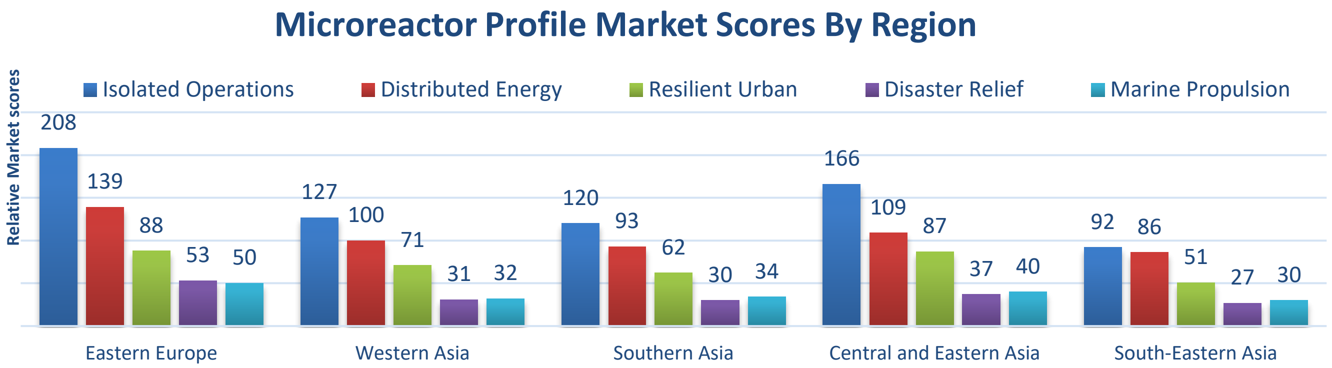
Results: Microreactor have potential to invigorate nuclear demand in existing markets and in developing economies


Microreactor Profile Market Scores By Region


Microreactor Profile Market Scores By Region

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FY-22 Updates

- Journal article "Prospects for Nuclear Microreactors: A Review of the Technology, Economics and Regulatory Considerations" currently in technical review for submittal to the ANS Nuclear Technology - Special Edition on Microreactors:
  - Differentiates microreactors from SMRs and their capacity to operate in isolated and distributed markets.
  - Defines new elements of "value" where decision-makers place importance on reliability and resiliency, flexibility, mobility, cogeneration, etc.
  - Identifies key enabling technologies needed to bring microreactors into emerging energy markets (e.g., micro-grids, ROCs, secure imbedded intelligence).
  - Describes key areas where regulators need data and sufficient designs to inform testing and rulemaking on safety, safeguards, and security.
  - Underscores the importance of local and regional data on energy needs.
- Bipartisan Infrastructure Bill (Sec. 40321) Draft Report to Congress
  - Focus on the value of microreactors in supporting resilience and carbon reduction goals of the DOE, and strategies for deployment at DOE facilities and with private industry.

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Any Questions?

Market report available at DOE OSTI at: https://www.osti.gov/biblio/1806274

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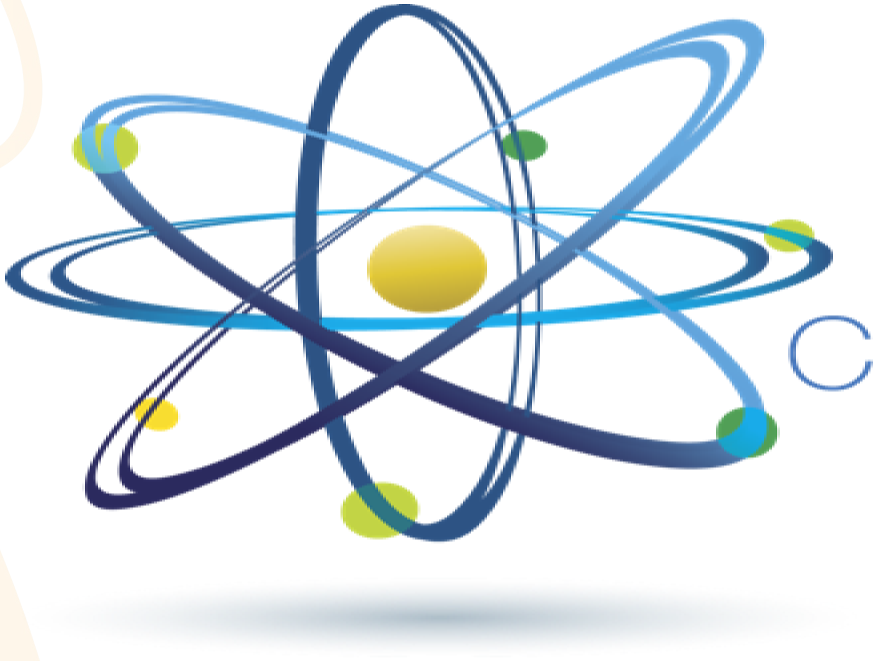
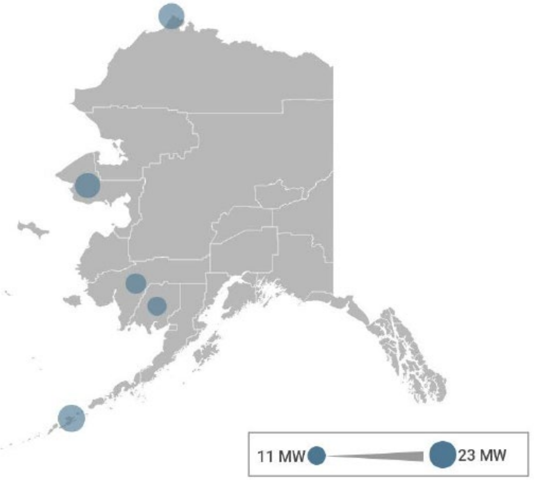
Backup Sides

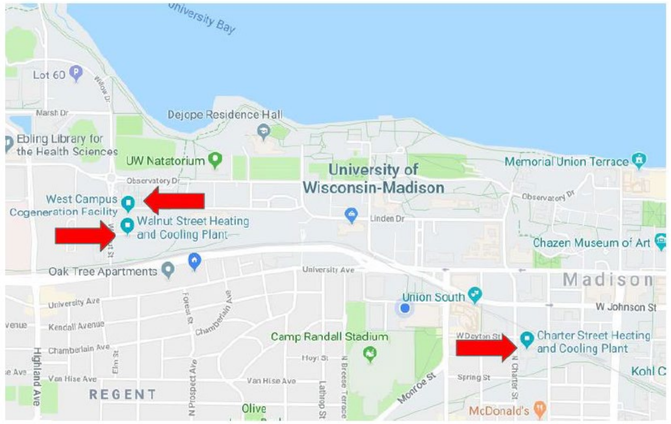


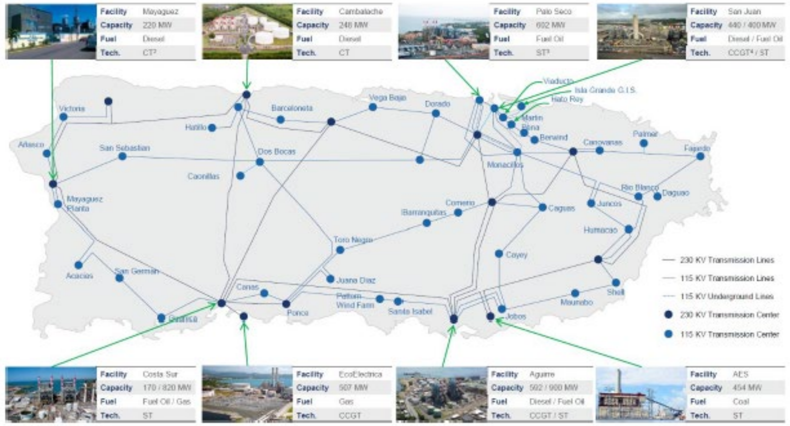
Clean. Reliable. Nuclear.

Microreactor Economic Analysis - Overview

- Scope overview. This work supports the understanding of the market and economic potential for microreactors in the U.S. and internationally.
- Why? Economic Performance and Market Analysis provides a techno-economic basis for support to industrial microreactor deployment and operation.
- How? Three studies managed by INL were independently conducted
  - U Alaska-Anchorage, U Wisconsin-Madison, and the Nuclear Alternatives Project in Puerto Rico.
  - INL summarized 3 studies and added international perspective in global market report.







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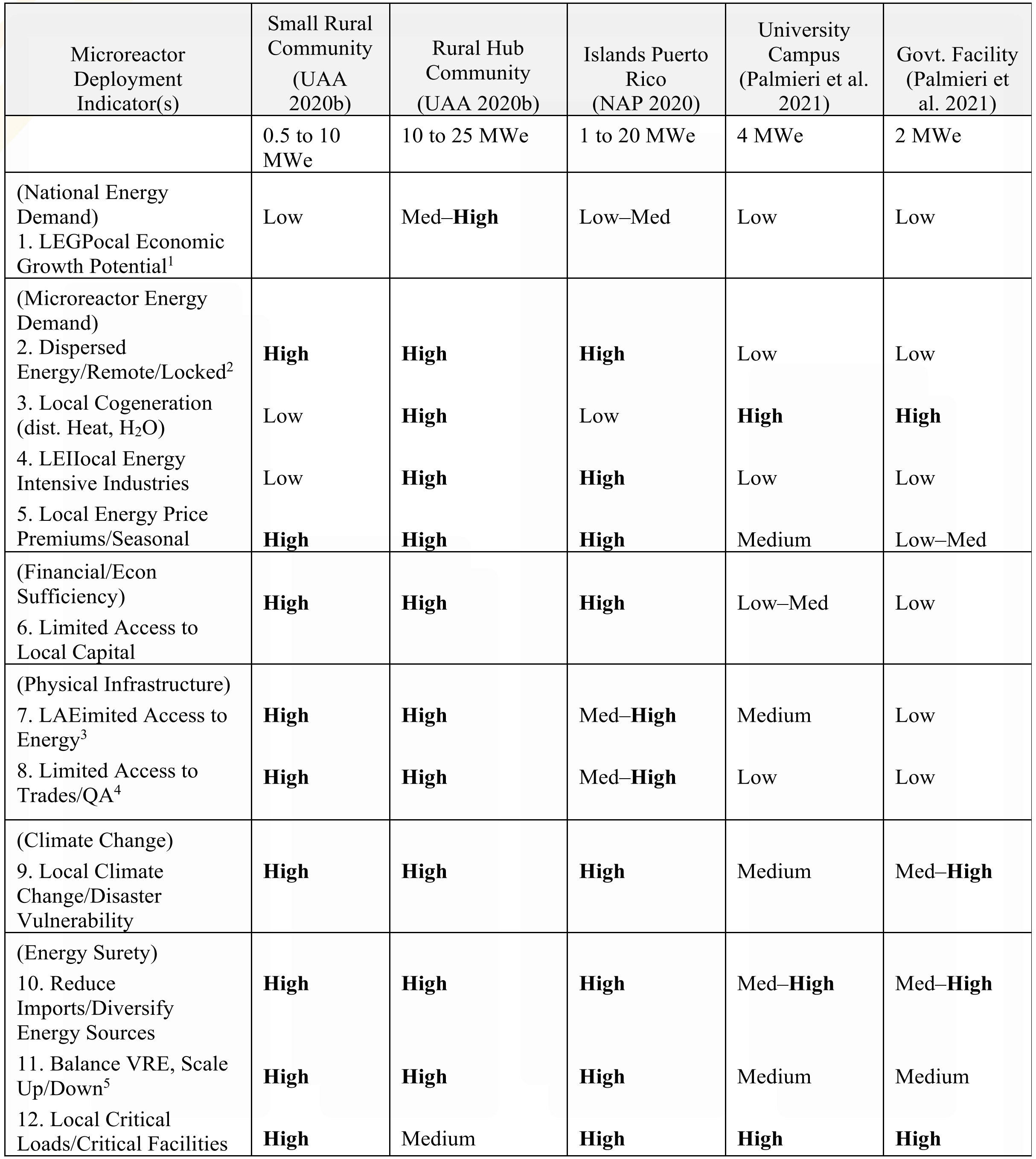
Global Market Analysis of Microreactors (INL/EXT-21-63214)

- Authors:
  - David Shropshire (Idaho National Laboratory)
  - Geoffrey Black (Boise State University)
  - Kathleen Araújo (CAES Energy Policy Institute, Boise State University)
- Objective:
  - The purpose of this report is to assesses the unique capabilities of microreactors and assess potential deployment in specific global markets in the 2030-2050 timeframe, with consideration for regulatory limits.

Analytical Methodology

- SMR Deployment Indicators are adapted for microreactors
  - Indicators are used to evaluate potential microreactor uses
  - Indicators are translated into microreactor design characteristics
- Use Cases used to derive general profile markets
- Global Market Assessment
  - Top-down global markets for advanced nuclear
  - Bottoms-up Assessment at country and regional level
- Qualitative insights and additional factors were evaluated (regulatory, risks, investment environment, etc.).



Microreactor Deployment Indicator(s)	Small Rural Community (UAA 2020b)	Rural Hub Community (UAA 2020b)	Islands Puerto Rico (NAP 2020)	University Campus (Palmieri et al. 2021)	Govt. Facility (Palmieri et al. 2021)
	0.5 to 10 MWe	10 to 25 MWe	1 to 20 MWe	4 MWe	2 MWe
(National Energy Demand) 1. LEGPocal Economic Growth Potential[1]	Low	Med–**High**	Low–Med	Low	Low
(Microreactor Energy Demand) 2. Dispersed Energy/Remote/Locked[2]	**High**	**High**	**High**	Low	Low
3. Local Cogeneration (dist. Heat, H_2O)	Low	**High**	Low	**High**	**High**
4. LEIlocal Energy Intensive Industries	Low	**High**	**High**	Low	Low
5. Local Energy Price Premiums/Seasonal	**High**	**High**	**High**	Medium	Low–Med
(Financial/Econ Sufficiency) 6. Limited Access to Local Capital	**High**	**High**	**High**	Low–Med	Low
(Physical Infrastructure) 7. LAEimited Access to Energy[3]	**High**	**High**	Med–**High**	Medium	Low
8. Limited Access to Trades/QA[4]	**High**	**High**	Med–**High**	Low	Low
(Climate Change) 9. Local Climate Change/Disaster Vulnerability	**High**	**High**	**High**	Medium	Med–**High**
(Energy Surety) 10. Reduce Imports/Diversify Energy Sources	**High**	**High**	**High**	Med–**High**	Med–**High**
11. Balance VRE, Scale Up/Down[5]	**High**	**High**	**High**	Medium	Medium
12. Local Critical Loads/Critical Facilities	**High**	Medium	**High**	**High**	**High**

Deployment Indicators are evaluated for each Use Case

–

Assess the relative importance and sensitivity

SMR Indicators were adapted for key microreactor roles

- Replacing fossil fuels particularly in remote applications and locations lacking centralized energy sources and transmission.
- On Islands to improve energy security (supply chain independence) and reliability.
- Federal Facilities to improve resilience and reduce dependence on backup diesel generators.
- Integrated in microgrids to increase resilience to mitigate extreme natural events (earthquakes, hurricanes, etc.).
- In distributed energy systems (in developing economies) with renewable sources and energy storage, and heating needs.
- As embedded energy systems in markets lacking power infrastructure

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Regulatory Considerations

- Microreactors have unique designs that NRC is not routinely familiar;
- Factory production will require access, control measures and safeguards protections;
- Shipping fueled reactors opens new questions on treaties, export controls, transit in international waters/airspace, radiation protection, etc.;
- Long-standing international agreements may require revisions, e.g., Convention for the Physical Protection of Nuclear Material, Nuclear Non-Proliferation Treaty, etc.;
- New security and safeguard scenarios and ability for rapid response from operational teams and external impact assessments need addressed;
- Development of new codes and standards for new designs;
- Remote and semi-autonomous operation will impact control room designs and impact security and safety by design approaches;
- Risk analysis will need to account for unique operational life cycle and reactor components.

Additional Considerations:

- Operational requirements (local skill sets) and local capabilities (used fuel storage);
- Lifecycle processes, including refueling, routine maintenance, and remediation and the ease of conducting them in remote areas;
- Adaptability or flexibility for changing energy systems (e.g., move reactors between mines);
- Community acceptance and perceptions over local control of energy systems, generally more positive than large reactors, particularly at military bases. The large number of unknowns influence perception at the technical level and among the general public.
- Resilience from supply chain disruption and other forces which could impact energy services;
- Local investment in energy system and community advocates;
- Availability of support networks to provide technical assistance throughout the life of the reactor.

To Summarize…

- In basic market terms, for microreactors to achieve deep penetration in markets will require achieving specific aggressive cost targets; markets not available to large nuclear plants in traditional centralized energy markets.
- Microreactors have potential to expand nuclear power’s contribution in North America and Western Europe, where there is little growth otherwise.
- Microreactors could help close the gap on zero carbon by 2050 by replacing fossil sources for electric and non-electric uses and support increased renewable shares.
- Microreactor technology may support energy resilience strategies for a variety of regions and applications.
- As research, development, and demonstration advance across a wide range of designs, near-term questions require regulatory address with respect to transporting microreactors and fuel, as well as novel safety, security, and safeguards considerations.

Observations about Competitiveness:

Isolated Operations:

- Costs competitive with diesel generators.
- Minimal on-site personal and semi-autonomous controls.
- Transportable to areas with limited access and infrastructure.
- Reliable with high-capacity factors, resilience to disruptions.
- Operate independently from the electric grid to supply highly resilient power for critical loads.
- Long lived fuel with long refueling cycles.
- No off-site power needed and minimal on-site construction in remote applications.
- Compatibility with local microgrids supporting facility operations.
- Compatibility with energy end-uses that are controlled through remote operation centers.

Distributed Energy Applications:

- Cost competitive in the local energy market.
- Ability to produce electricity and non-electric products.
- Flexible power conversion system for energy integration with wind and solar.
- Ability to scale to meet changing loads over time, at multiple voltage outputs.
- Enhanced security and safeguards for deployment in global applications.
- Compatibility with mini- and micro- grids supporting local and regional energy markets.

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DOE-NE Microreactor Program

Licensing and Regulatory Development

Jason Christensen | Idaho National Laboratory

Winter Review Meeting, March 3-4, 2022

Objectives for Microreactor Regulatory Development

- Address and resolve key regulatory framework and licensing technical issues that directly support the “critical path” to advanced reactor demonstration and deployment
- Provide recommendations and solutions to regulatory issues associated with the program
- Develops licensing and regulatory strategies to enable future microreactor deployments
- Program activities include a particular focus on addressing and resolving regulatory uncertainties in the next 1-2 years that challenge near-term (5-7 years) deployments
- In essence, the program is seeking ways to provide impactful DOE funding for cross-cutting industry-identified experimental work at DOE complex labs that will support the near-term licensing of micro-reactors

FY21 Regulatory Research Plan

- The Regulatory Research Plan (RRP) generated in FY21 was a significant driver in the work being performed in FY22 and beyond
- The RRP surveyed major industry organizations and reactor developers to determine their most critical regulatory needs that have not yet been addressed by NRC at this time
- Specifically, this survey asked the organizations to rank the following items by criticality:
  - Autonomous and Remote Control/Monitoring
  - Grid Interaction
  - Factory Assembly
  - Transportation
  - Staffing
  - Digital Controls
  - Instrumentation
  - Modeling and Simulation
  - Siting and Environmental Impact
  - Security and Safeguards

MRP Microreactor Program

FY21 RRP Results

- The initial survey results were grouped into bands based on importance and time criticality
- The areas of highest priority are band 1 and are needed before subsequent bands

Band	Topic Area
1	Autonomous and Remote Control/Monitoring
	Modeling and Simulation
2	Transportation
	Siting and Environmental Impact
	Security and Safeguards
	Factory Assembly
3	Operations, Maintenance, and Security Staffing
	Grid Interaction
	Digital Controls
	Instrumentation

MRP Microreactor Program

Manufacturing Licenses for Microreactors

- Some microreactor vendors have stated the desire to construct their entire reactor in a factory setting under a manufacturing license (some including factory fueling)
  - Allows for many duplicate reactors to the fabricated in the same facility with no location change
  - Reduces complexity of on-site assembly and construction
  - These microreactors would then be shipped (fueled or unfueled) to an operating site licensed under 10CFR Part 50/52/53
    - In most cases, the used microreactors would be returned to the factory for refurbishment or decommissioning
    - In some cases, the used microreactors would be transported to other locations for installation and re-use

Conclusions to the RRP and Path Forward

- The survey indicated the two highest areas of need as autonomous operations and/or remote control/monitoring as well as modeling and simulation
- After review staff determined that significant work was being performed in those areas
- The next band of survey results contained two items of significant interest: transportation and factory assembly/manufacturing licenses.
- These two items became our focus for FY22 and beyond

History of Manufacturing Licenses

- Manufacturing licenses date back to the early 1970’s when the Atomic Energy Agency (AEA) developed Appendix M to 10 CFR Part 50
  - Would still be part of a construction permit
  - This did NOT constitute a final design certification by NRC

- With the development of 10 CFR Part 52, NRC initially did not include manufacturing licenses. This would change during later revisions
  - Subpart F was developed to house the manufacturing license regulations
  - Unlike Part 50, a Final Safety Analysis Report (FSAR) was required for a manufacturing license
  - This would also require the inclusion of inspections, tests, analyses, and acceptance criteria (ITAAC) that would be inspectable by NRC

FY22 Activities: Manufacturing Licenses and Transportation

- Some microreactor vendors have stated the desire to construct their entire reactor in a factory setting under a manufacturing license (some including factory fueling)
  - Reduces complexity of on-site assembly and construction
  - These microreactors would then be shipped (fueled or unfueled) to an operating site licensed under 10CFR Part 50/52/53
- Currently, the draft regulation for 10CFR Part 53 Subpart E addresses traditional manufacturing licenses but does not address Part 70 (SNM possession and use), Part 71 (transportation), or Part 72 (spent fuel storage)
- NEI White Paper from July 2021 provided recommendations to NRC staff on how to address these needs
- INL report (due March 2022) will provide a recommendation from INL/ORNL staff on how to address these needs
  - INL/ORNL staff will then draft a report (due September 2022) that discusses and provides recommendations for transportation of a fueled or unfueled microreactor from the factory to the operational site

MRP Microreactor Program

Manufacturing Licenses in 10 CFR Part 53

- While still under development, 10 CFR Part 53 will contain manufacturing license regulations under Subpart E, “Construction and Manufacturing”. The final draft of this Subpart has not been fully completed at this time
- This will cover quality control and post-manufacturing testing/inspections (similar to ITAAC from Part 52)
- Initially, the draft regulation for 10CFR Part 53 Subpart E addresses traditional manufacturing licenses but does not address Part 70 (SNM possession and use), Part 71 (transportation), or Part 72 (spent fuel storage)
- Since the report was submitted in February, the NRC has decided to include information about factory-fueling of a microreactor prior to shipment
  - Transportation (Part 71) and spent fuel storage (Part 72) are not being considered for inclusion at this time

NEI White Paper: “Proposed Approach for Manufacturing License Requirements in 10 CFR Part 53”

- NEI’s white paper broke the manufacturing of microreactors into eight business cases
  - These cases included unfueled, factory fueled, factory-fueled and tested manufacturing of microreactors with no current contract/demand
  - Other cases were considered as well but will not be discussed here
- NEI provided three major options for the Part 53 Subpart E rulemaking
  - Part 53 Only- all necessary sections from 10 CFR would be included, even fitness for duty, material control and accounting, etc.
  - Part 53 Centric- all design, licensing, manufacturing, transporting, and operations would fall under this option
  - Part 53 Limited-Part 53 would only address reactor delivery safety requirements in an FSAR

- NEI chose the Part 53 Limited option as their recommendation

MRP Microreactor Program

Microreactor Program Recommendations

- INL/ORNL staff reached the same basic three options after research and review
- Microreactor Program staff recommend a path similar to the Part 53 Only Option, with some exceptions
  - Parts 70-73 would be addressed in Part 53. These reactors are new technology and the incorporation of these would allow changes to be made that would not affect the current operating fleet. Additionally, it would allow designers to take advantage of technological advances in their reactor type
- The introductory report written by INL and ORNL staff will be modified through the end of FY22
- The final report (due in September 2022) will contain updates of this information but will begin to discuss the transportation aspects of shipping a microreactor to its intended use location

MRP Microreactor Program

Transportation of Fueled or Unfueled Microreactors

- Transportation:
  - There are multiple stages of transportation throughout the life of a microreactor
    - From factory to use site (fueled but not yet operational)
    - Between use sites (post-operation)
    - From use site to disposition process facility (spent fuel for disposal)

  - Each of these stages of transport are unique and will require the applicant to meet different regulations, such as:
    - Transport Container Design
    - Shielding for each operational stage
    - Shipping Type (air, train, ship, truck)
    - Emergency response

MRP Microreactor Program

FY23 Proposal: Transition from Shipping to Operational Status

- Microreactors are slated to have modular construction techniques that will ship major components or possibly near complete units from the factory to approved siting locations
  - Reduces complexity of on-site assembly and construction
- The transition from shipment regulations (10CFR Part 71) to an operating license under 10CFR Parts 50/52 is not currently addressed by regulations
- 10CFR Part 53 will need to address this missing piece (likely under Subpart E, which contains construction aspects and inspections, tests, analyses, and acceptance criteria)

- **Key Question:** What regulatory process will be used during the transition of a mobile reactor from 10 CFR Part 71 to 10CFR Part 50/52 or Part 53?
  - **Deliverable:** Regulatory Strategy Report that outlines the transition that could be submitted to NEI/NRC for comment or endorsement

Conclusions

- Microreactor regulatory staff continue to seek new and updated needs to support the development and deployment of microreactors
- For more information, request a survey, or to provide specific research input, please contact:

Jason Christensen
INL Regulatory Support Engineer
Jason.Christensen@inl.gov

MRP Microreactor Program

Flexible Siting Criteria and Staff Minimization for Micro-Reactors

MITei
MIT Energy Initiative

NSE
Nuclear Science
and Engineering
science : systems : society

THE PROJECT TEAM


Isabel Naranjo
(grad)


Edward Garcia
(grad)


Carmen Sleight
(grad)


Lucy Nester
(UG)


Santiago Andrade
(grad)


Jacopo Buongiorno
(PI, NSE)

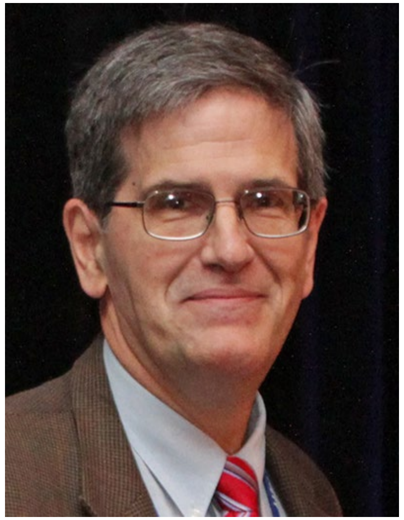

Edward Lau
(NRL)


Sara Hauptman
(NRL)


Neil Todreas
(NSE)

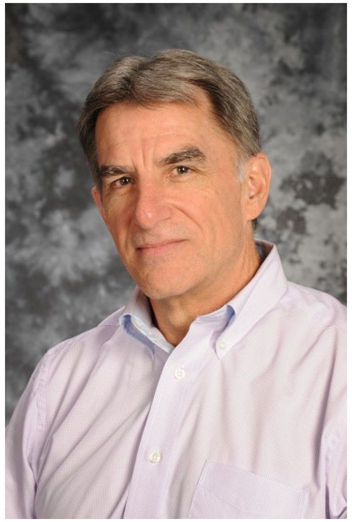

Federico Antonello
(postdoc)

THE ADVISORY COMMITTEE



Michael Corradini
(U-Wisconsin)

Matthew Smith
(Westinghouse)



James Kinsey
(INL, Coastal Technical Services)

ECONOMIC IMPERATIVES FOR MICROREACTORS

- To access large markets, microreactors must be licensable for deployment near and within population centers ⇐

- LCOE and LCOH analysis suggests that microreactors can meet the heat and electricity cost targets for large markets, if:
  - ➢ Power output is maximized, within microreactor constraints (e.g., truck transportability, passive decay heat removal)
  - ➢ Staff is in the 0.5-1.5 FTE/MW range ⇐
  - ➢ Enrichment <10% and burnup >20 $\mathrm{MWd/kg_U}$
  - ➢ Microreactor fabrication cost (excluding fuel) <5000 $/kW
  - ➢ Discount rate <10 %/yr

⇐ focus of this project

PROJECT OBJECTIVES

- Develop siting criteria that are tailored to micro-reactors deployable in densely-populated areas, e.g., urban environments.
- Identify optimal licensing path for micro-reactors in Part 50 and Part 52 framework
- Conceptualize a model of operations and security for micro-reactors that would minimize the staffing requirements, and thus reduce the cost of electricity and heat generated by these systems.
- Develop a new Type B transport cask design for fueled micro-reactors *(NEW)*

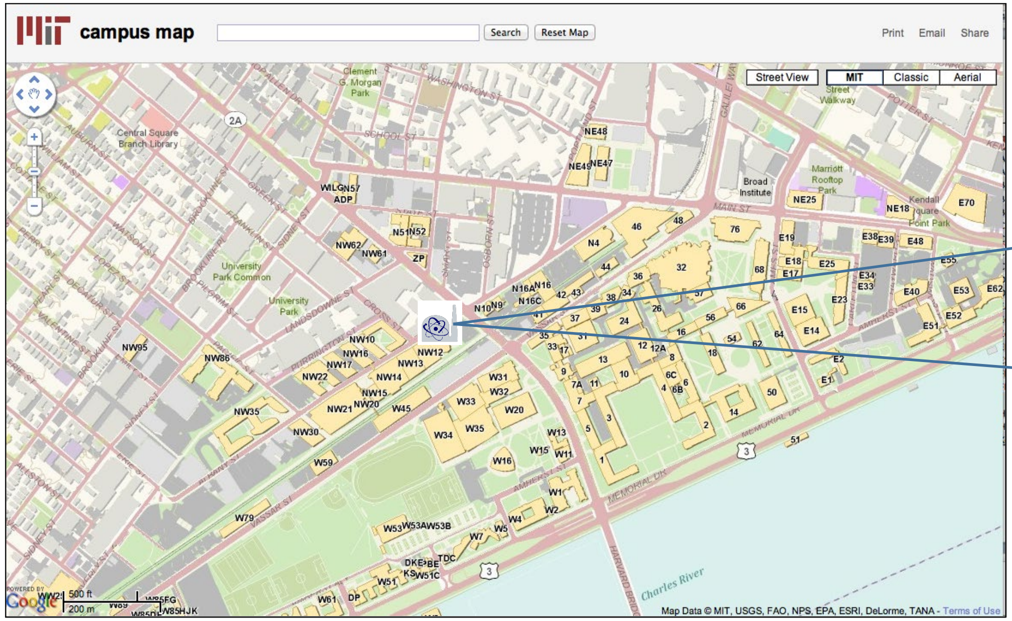
APPROACH

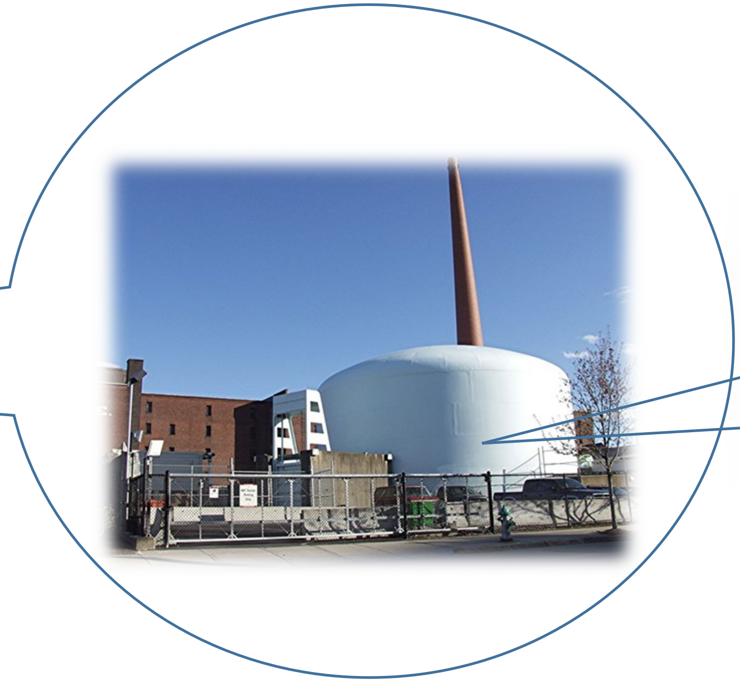
- Compare MIT nuclear reactor (MITR) with leading micro-reactor concepts, and evaluate whether and how the MITR design basis (e.g., inherent safety features, engineered safety systems, source term, emergency planning and emergency operating procedures) and associated regulations may be applicable to micro-reactors.

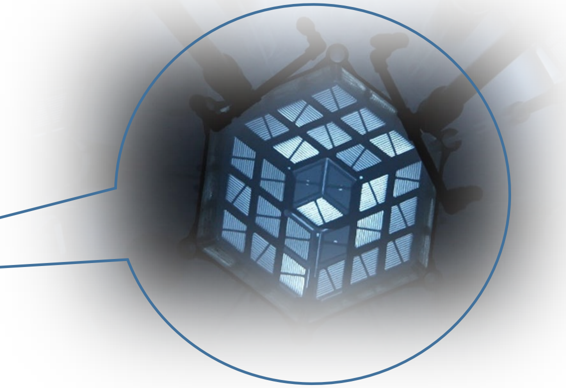
- Review the MITR experience and requirements, as well as survey the innovations in autonomous control technologies (e.g., machine learning) and monitoring (e.g., advanced sensors, drones, robotics) that may permit a dramatic reduction in staffing at micro-reactor installations.

THE MITR

MITR is an urban micro-reactor:
- low power (6 MWt)
- 24/7 ops
- ultra-safe

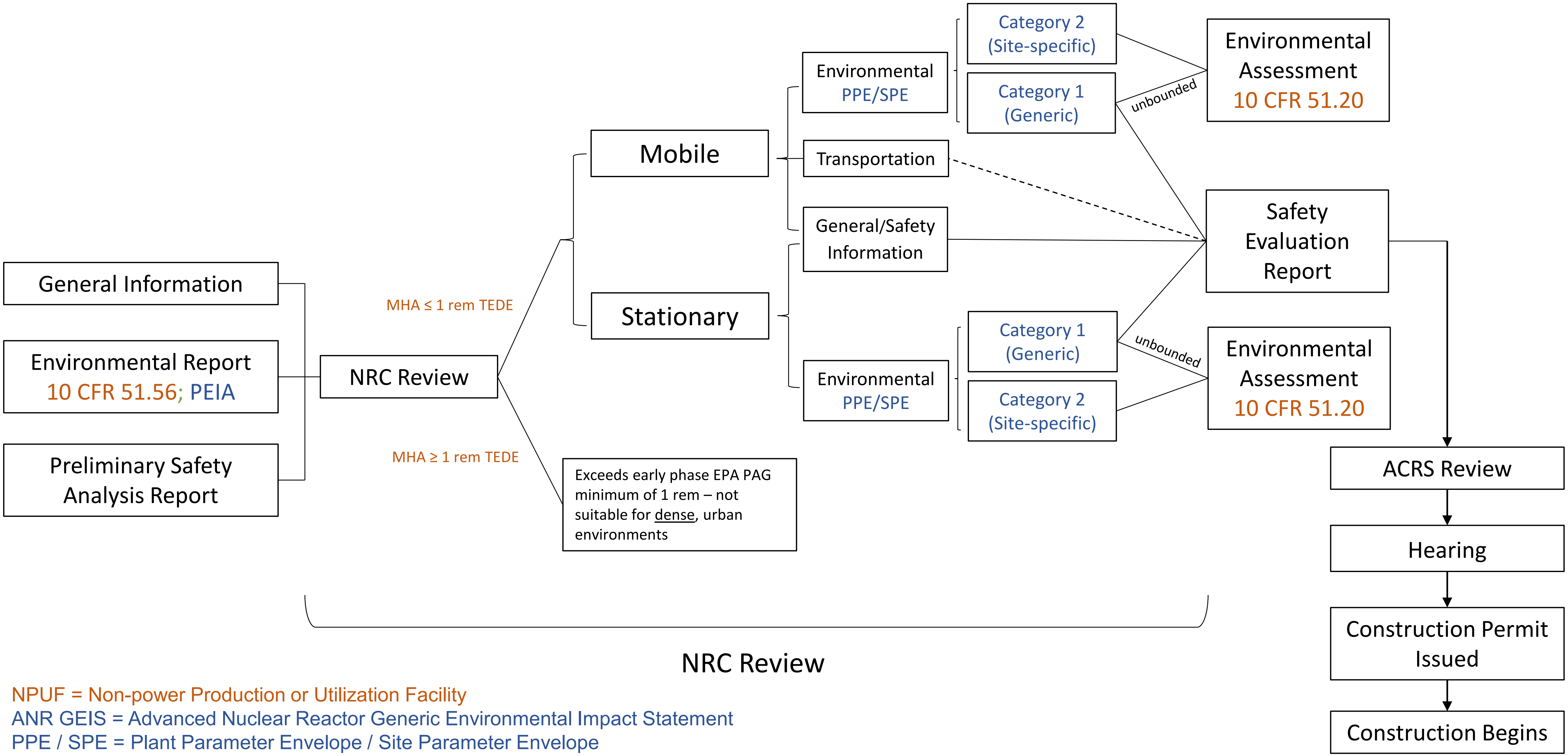






But there are major differences:
- the mission is research (vs. commercial)
- unsuitable for heat utilization and electricity generation (<60°C core outlet temperature)
- frequent refueling (every 10 weeks)
- non-transportable
- large staff (operations + research + admin = 60 FTEs)

Modified Part 50 for Microreactors as NPUFs



General Information

Environmental Report
10 CFR 51.56; PEIA

Preliminary Safety Analysis Report

NRC Review

MHA ≤ 1 rem TEDE

MHA ≥ 1 rem TEDE

Mobile

Stationary

Exceeds early phase EPA PAG minimum of 1 rem – not suitable for dense, urban environments

Environmental PPE/SPE

Transportation

General/Safety Information

Environmental PPE/SPE

Category 2 (Site-specific)

Category 1 (Generic)

Category 1 (Generic)

Category 2 (Site-specific)

unbounded

unbounded

Environmental Assessment
10 CFR 51.20

Safety Evaluation Report

Environmental Assessment
10 CFR 51.20

ACRS Review

Hearing

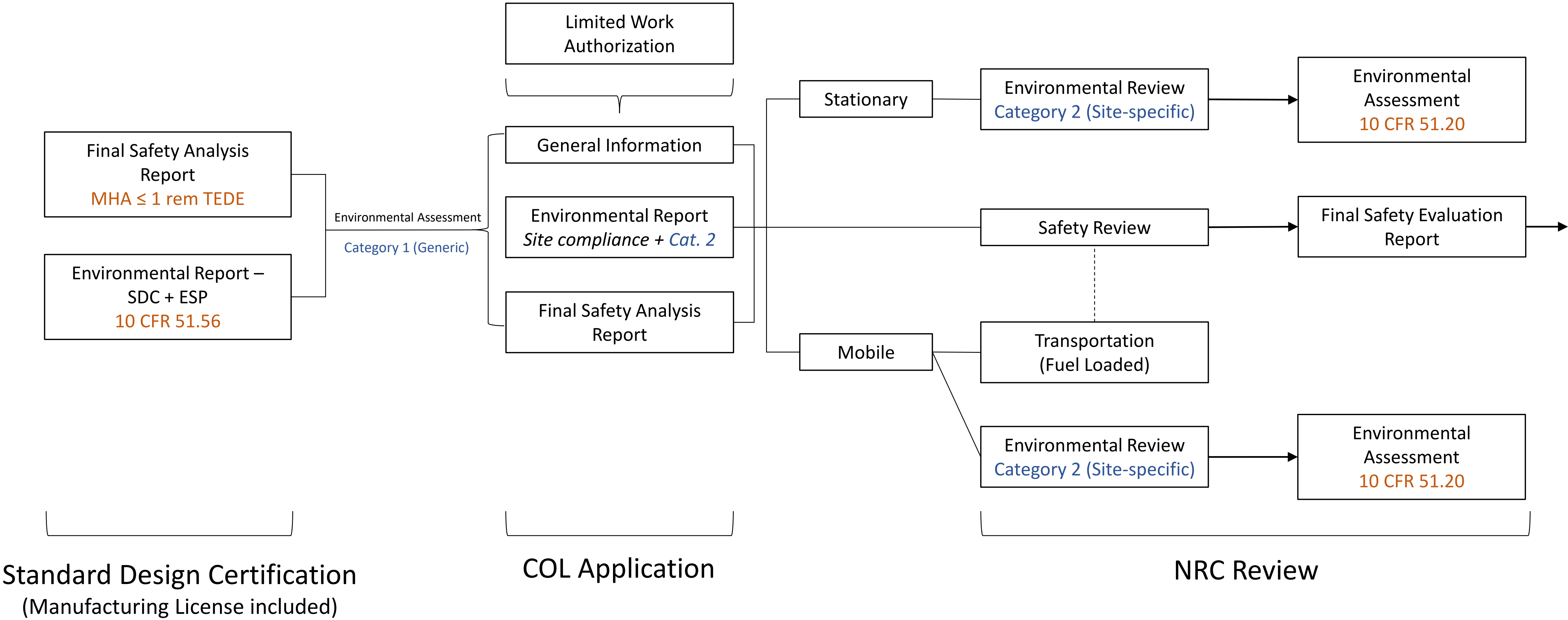
Construction Permit Issued

Construction Begins

NRC Review

NPUF = Non-power Production or Utilization Facility
ANR GEIS = Advanced Nuclear Reactor Generic Environmental Impact Statement
PPE / SPE = Plant Parameter Envelope / Site Parameter Envelope
PEIA = Preliminary Environmental Impact Assessment

Modified Part 52 for Microreactors as NPUFs



Final Safety Analysis Report
MHA ≤ 1 rem TEDE

Environmental Report – SDC + ESP
10 CFR 51.56

Environmental Assessment
Category 1 (Generic)

Limited Work Authorization

General Information

Environmental Report
Site compliance + Cat. 2

Final Safety Analysis Report

Stationary

Mobile

Environmental Review
Category 2 (Site-specific)

Safety Review

Transportation (Fuel Loaded)

Environmental Review
Category 2 (Site-specific)

Environmental Assessment
10 CFR 51.20

Final Safety Evaluation Report

Environmental Assessment
10 CFR 51.20

Standard Design Certification
(Manufacturing License included)

COL Application

NRC Review

DC: 12 months NRC Review: <12 months

*NPUF
ANR GEIS

BOTTOM-UP EVALUATION OF O&M STAFFING NEEDS

Goal: to demonstrate the minimum staffing level achievable with no technological and regulative constraints

For each planned O&M task, we evaluated:

- frequency, # FTEs involved, task duration

- possible automation technology

MITR planned maintenance tasks - example

Task name	Brief description	Frequency [#/year]	# FTEs involved	Duration [h]	FTE time per year (C*D*E) [h/year]	Possible automation technology
Emergency Cooling System test	Test of the ECCS to make sure adequate flow rate	1	4	4	16	Out of scope: task not needed for MR
Reactor Building Leak Rate	Test to make sure containment is air-tight	0,5	20	24	240	Smart sensors

Worst case

~7 FTEs
onsite

Assumptions

Staffing needs in FTEs/year are divided into five categories:

- Planned Maintenance – derived analytically from the study of their systems
- Unplanned Maintenance – hypothesis: 25% of planned maintenance
- Operation – hypothesis: 1 person, 24/7 (equivalent to 5 FTEs), simultaneously monitoring 8 MR
- Administrative – hypothesis: 1 FTE in charge of 8 MR (1 FTE works on 1 daily shift only, not 24/7)
- Engineering – hypothesis: 10% of maintenance

Staffing needs comparison - FTEs/year

	MITR	Gas V16 2.4 MWe	Aero-derived 1.5 MWe	Aurora
Maintenance - nuclear specific	0,3	N/A	N/A	0,1
Maintenance - total	0,7	0,2	0,1	0,4
Operation	10,0	0,6	0,6	0,6
Administrative*	10,0	0,1	0,1	0,1
Engineering*	4,0	0,0	0,0	0,0
Total - nuclear specific	14,3	N/A	N/A	0,8
Total FTEs/year	**24,7***	**1,0**	**0,9**	**1,2**

*Majority of MITR staff work is related to set up and management of experiments

Best case

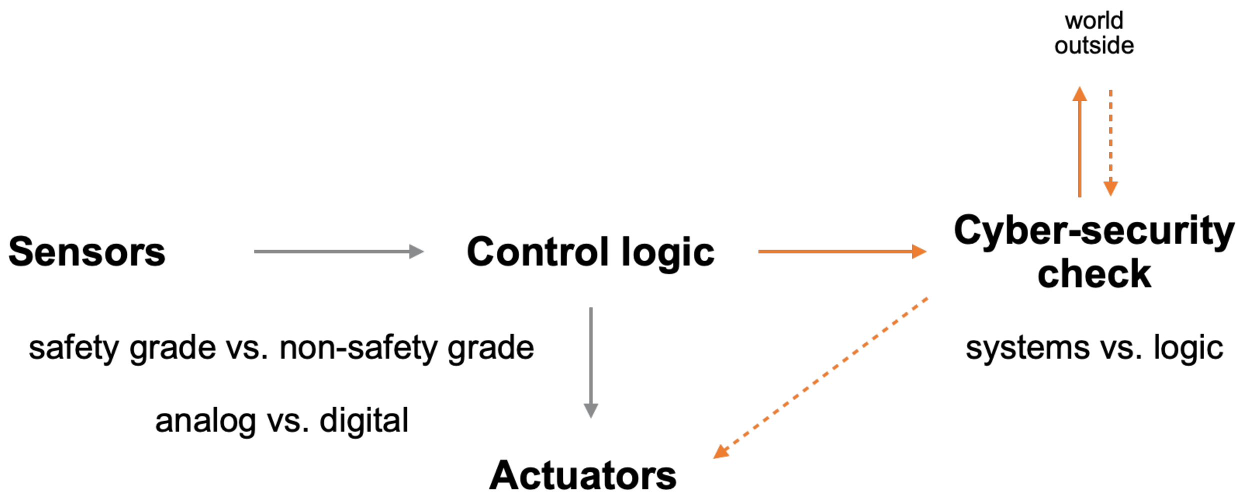
~ 1 FTE
mostly offsite

INSTRUCTRUMENTATION AND CONTROL FOR MRs

Goal: to determine a fully comprehensive set of I&C that allows to operate at the minimum staffing level

Sensors listed by

- Position: e.g., reactor core, BOP, site boundary
- Scope: e.g., power measurement, structural health monitoring, intrusion detection
- Parameter measured: e.g., n flux, temperature, vibration spectrum
- Type: e.g., self-powered n detectors, thermocouples, fiber optics
- Goal: safety, autonomous operation, predictive maintenance, DT data feed
- Included in: demonstration units, FOAK, commercial fleet
- I/O: analog, digital
- Other features: e.g., TRL, expected lifetime, maintenance/replacement needs



Next steps

- Business case: is it cheaper to operate with more operators onsite and less technology or the opposite?
- Scenarios evaluation: which scenario is more recommendable for the first units? Which for the fleet? Which are the regulatory constraints?

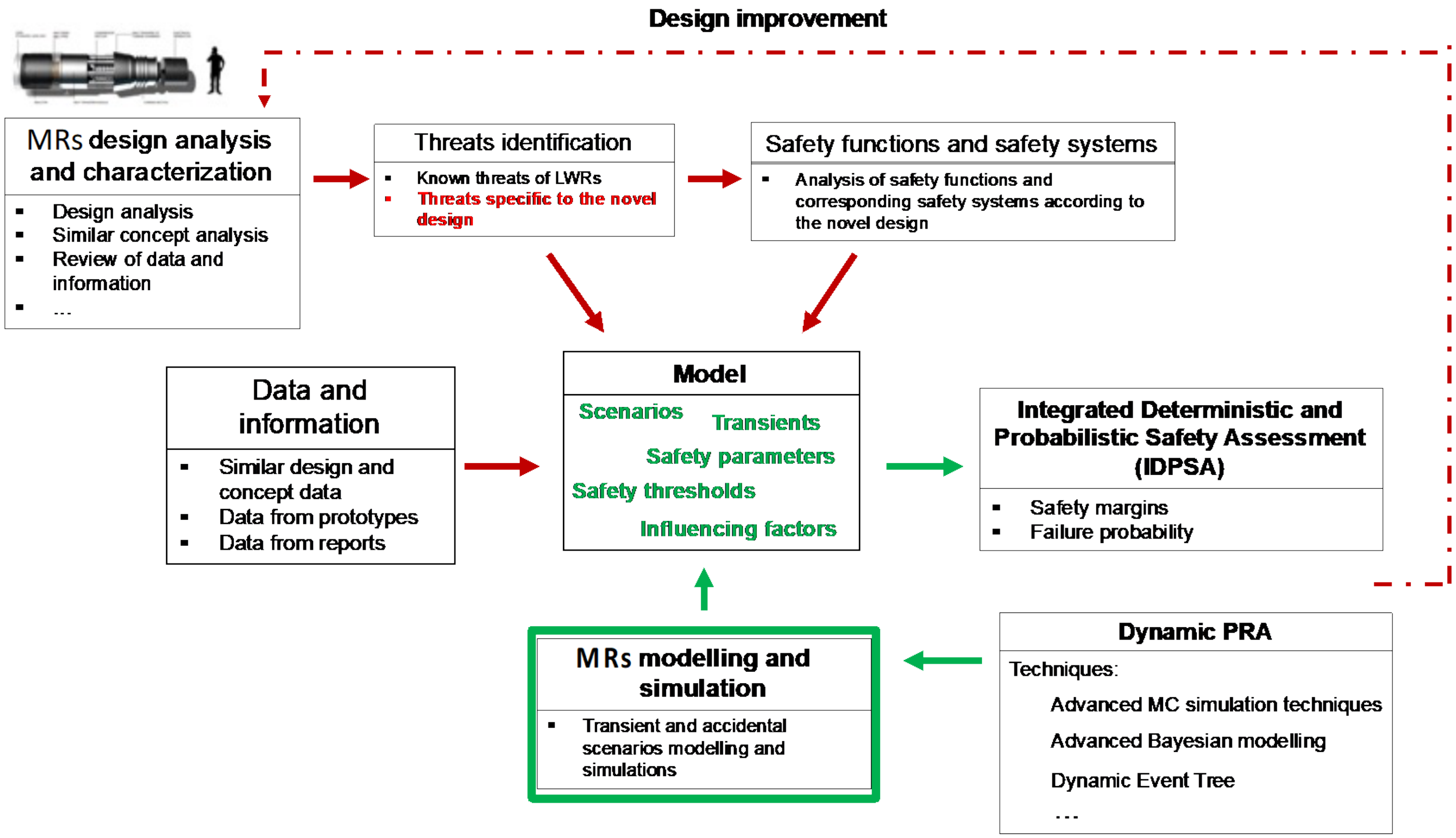
ADVANCED SAFETY ASSESSMENT OF MICROREACTORS

Goal: Develop a general framework to investigate microreactors threats and vulnerabilities, and assess the risk quantitatively

MRs: relatively novel design

Unknown threats

Advanced safety assessment



Design improvement

MRs design analysis and characterization

- Design analysis
- Similar concept analysis
- Review of data and information
- ...

Threats identification

- Known threats of LWRs
- Threats specific to the novel design

Safety functions and safety systems

- Analysis of safety functions and corresponding safety systems according to the novel design

Data and information

- Similar design and concept data
- Data from prototypes
- Data from reports

Model

Scenarios

Transients

Safety parameters

Safety thresholds

Influencing factors

Integrated Deterministic and Probabilistic Safety Assessment (IDPSA)

- Safety margins
- Failure probability

MRs modelling and simulation

- Transient and accidental scenarios modelling and simulations

Dynamic PRA

Techniques:

Advanced MC simulation techniques

Advanced Bayesian modelling

Dynamic Event Tree

...

ADVANCED SAFETY ASSESSMENT OF MICROREACTORS

Main steps and ongoing work

Step	Brief description	Expected output	Status
Qualitative safety evaluation	MRs design analysis and identification of threats, hazards and accidental scenarios of interest.	Characterization of traditional LWR threats/hazards to consider for the MRs, and novel threats/hazards proper of the MRs	A preliminary analysis has been performed and an initial set of accidental scenarios of interest have been identified
Simulation model development	Development of a Best Estimate (BE) simulation model	BE simulation model allows investigating the behavior of MRs during accidental scenarios, and considering the parameters uncertainty in the model	A preliminary simulation model has been developed
Quantitative safety assessment	Development of a safety framework that embeds the BE simulation model and the systematic PRA framework to assess the risk quantitatively	Systematic risk insights such as: *a*) probabilistic safety margins; *b*) components failure probabilities; *c*) analysis of interactions and dependencies among systems, structures and components.	Ongoing

Evaluation of micro-reactor requirements and performance in an existing well-characterized micro-grid

Project 20-19693

Lucas Wodrich, Alvin Lee
Caleb S. Brooks, Tomasz Kozlowski
University of Illinois

John Hanson
Oklo Inc.

March 3, 2022

Project Purpose:

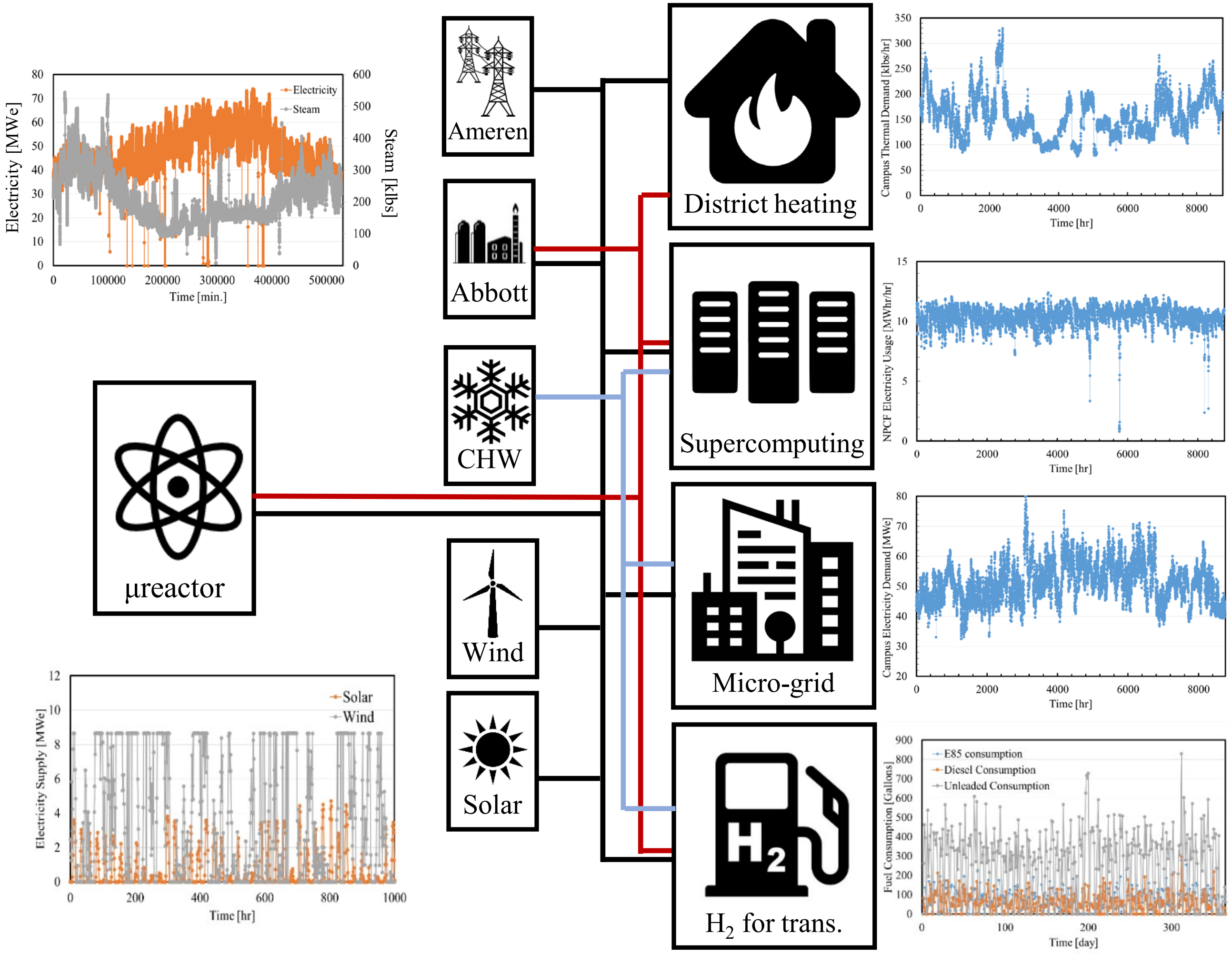
to quantify the opportunities and challenges of operating micro-reactors in populated, decentralized power generation environments and the potential for deployment in established micro-grids with diverse power generation sources.

Project Objectives:

1) Develop integrated system modeling of micro-reactor applications,
2) Incorporate available data to validate modeling,
3) Simulate normal and bounding events
4) Determine economic performance requirements across applications,
5) Identify operational requirements and opportunities across applications.
6) Determine the scalability of micro-reactor deployment at campuses and other existing micro-grids.

Overview of UIUC Campus Microgrid

- Electrical
  - 55 MW$_e$ average demand(Peak 80 MW$_e$)
  - Blue Waters Supercomputer up to 15 MW$_e$
  - Wind: ~25,000 MWhr/yr
  - Solar: ~27,200 MWhr/yr
  - Chillers: ~20 MW$_e$ peak
- Thermal
  - >50 MW$_{th}$ average demand
  - High P steam relatively constant,
  - Low P steam varies with Temp and RH
  - 6 Chilled water plants (2 steam, 21 electric)
  - Energy storage (6.5 million gallons chilled water)
- Transportation
  - Campus fleet ~ 800 gallons/day
  - Campus bus system: up to 3,400 gallons/day
  - Bus system already investing in 10 new H$_2$ busses



Data Overview

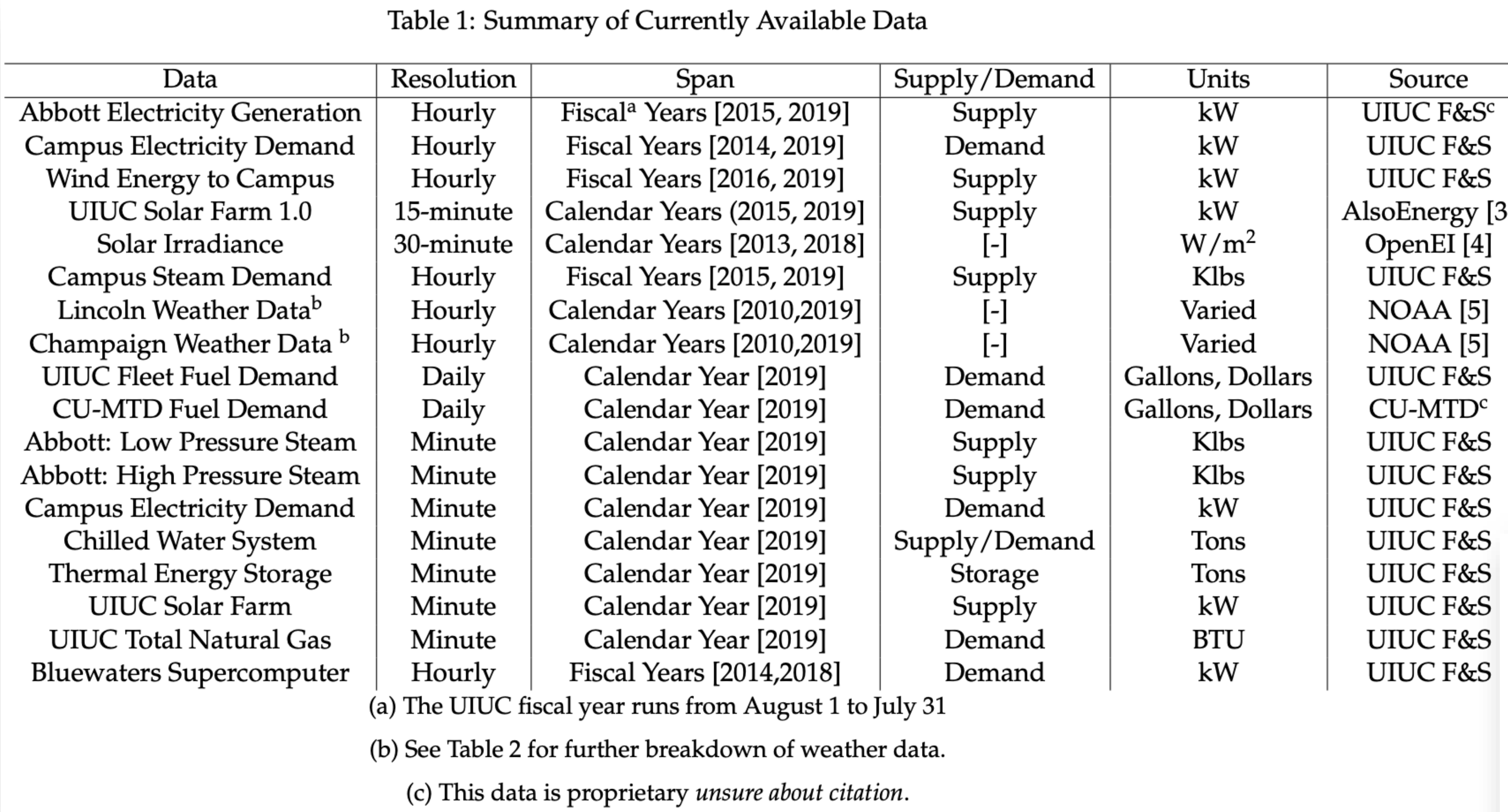


Table 1: Summary of Currently Available Data

Data	Resolution	Span	Supply/Demand	Units	Source
Abbott Electricity Generation	Hourly	Fiscal[a] Years [2015, 2019]	Supply	kW	UIUC F&S[c]
Campus Electricity Demand	Hourly	Fiscal Years [2014, 2019]	Demand	kW	UIUC F&S
Wind Energy to Campus	Hourly	Fiscal Years [2016, 2019]	Supply	kW	UIUC F&S
UIUC Solar Farm 1.0	15-minute	Calendar Years (2015, 2019]	Supply	kW	AlsoEnergy [3]
Solar Irradiance	30-minute	Calendar Years [2013, 2018]	[-]	W/m^2	OpenEI [4]
Campus Steam Demand	Hourly	Fiscal Years [2015, 2019]	Supply	Klbs	UIUC F&S
Lincoln Weather Data[b]	Hourly	Calendar Years [2010,2019]	[-]	Varied	NOAA [5]
Champaign Weather Data [b]	Hourly	Calendar Years [2010,2019]	[-]	Varied	NOAA [5]
UIUC Fleet Fuel Demand	Daily	Calendar Year [2019]	Demand	Gallons, Dollars	UIUC F&S
CU-MTD Fuel Demand	Daily	Calendar Year [2019]	Demand	Gallons, Dollars	CU-MTD[c]
Abbott: Low Pressure Steam	Minute	Calendar Year [2019]	Supply	Klbs	UIUC F&S
Abbott: High Pressure Steam	Minute	Calendar Year [2019]	Supply	Klbs	UIUC F&S
Campus Electricity Demand	Minute	Calendar Year [2019]	Demand	kW	UIUC F&S
Chilled Water System	Minute	Calendar Year [2019]	Supply/Demand	Tons	UIUC F&S
Thermal Energy Storage	Minute	Calendar Year [2019]	Storage	Tons	UIUC F&S
UIUC Solar Farm	Minute	Calendar Year [2019]	Supply	kW	UIUC F&S
UIUC Total Natural Gas	Minute	Calendar Year [2019]	Demand	BTU	UIUC F&S
Bluewaters Supercomputer	Hourly	Fiscal Years [2014,2018]	Demand	kW	UIUC F&S

(a) The UIUC fiscal year runs from August 1 to July 31

(b) See Table 2 for further breakdown of weather data.

(c) This data is proprietary *unsure about citation*.

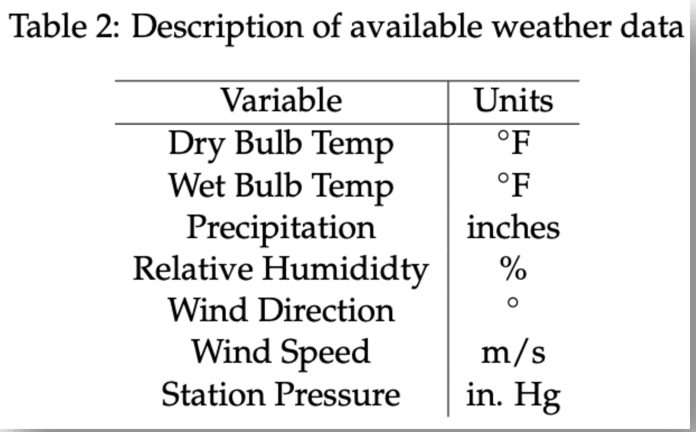


Table 2: Description of available weather data

Variable	Units
Dry Bulb Temp	°F
Wet Bulb Temp	°F
Precipitation	inches
Relative Humididty	%
Wind Direction	°
Wind Speed	m/s
Station Pressure	in. Hg

Overview of UIUC Campus Grid Emissions

Scope	Scope Definition	Emissions (MTCO2e; %)	Campus Energy Source %	Campus Electricity %
1	Emissions produced on campus within UIUC control	195,459; 45.1%	80%*	43.10%
2	Emissions from purchased electricity	183,595; 42.3%	20%	56.90%
3	Emissions from off campus university activities	54,743; 12.6%	N/A	N/A

*Calculated from fuel consumption

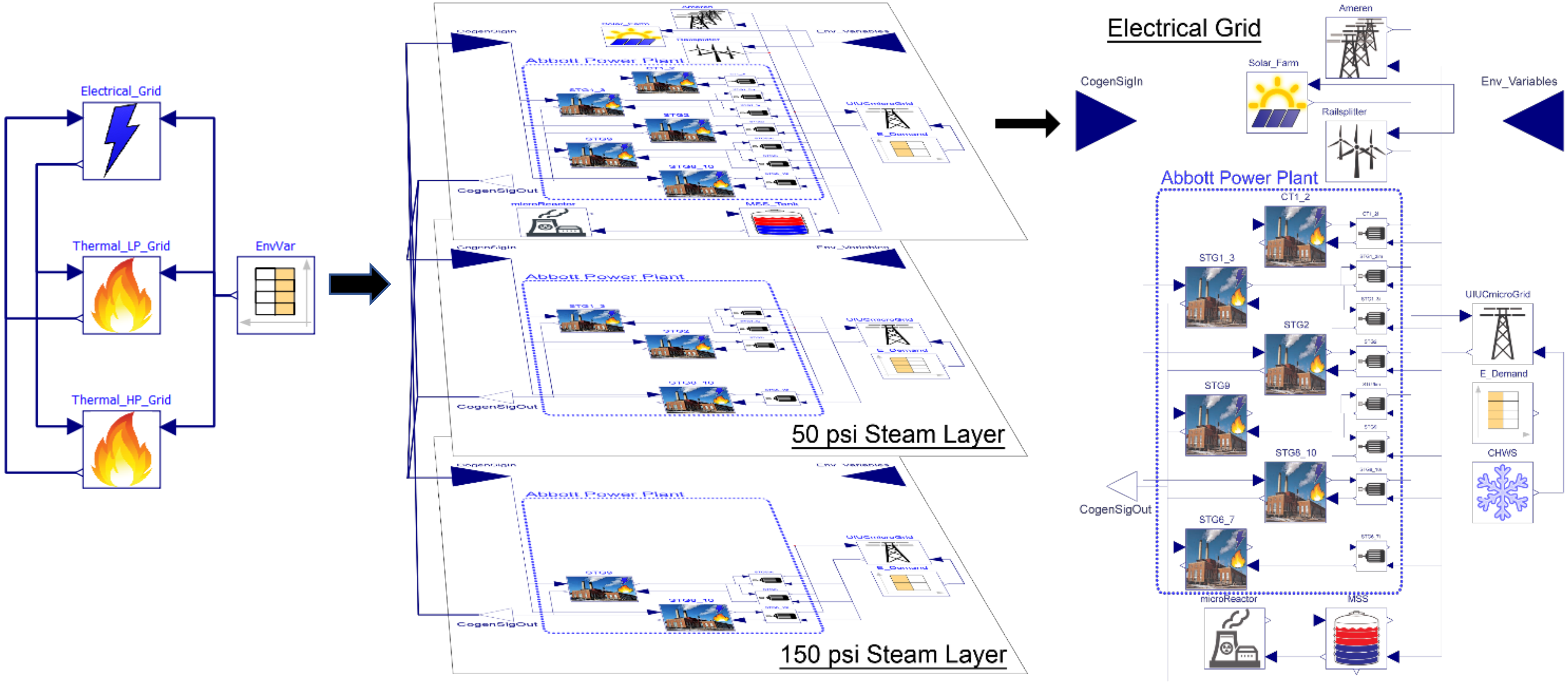
Ameren Energy mix:

Coal	Nuclear	Renewables	Natural Gas
69%	25%	5%	1%

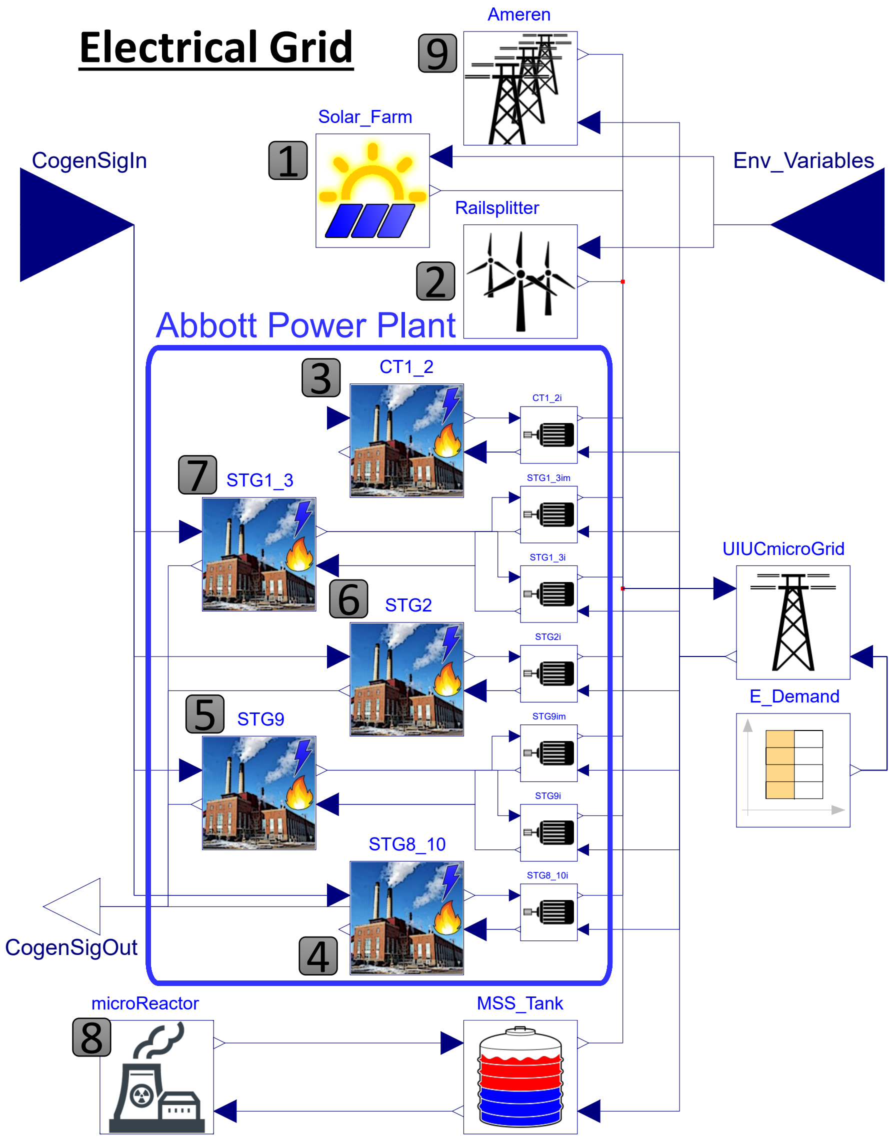
Campus Energy mix:

Natural Gas	Coal	Solar	Wind
89%	6%	2.5%	2.5%

Microgrid Model

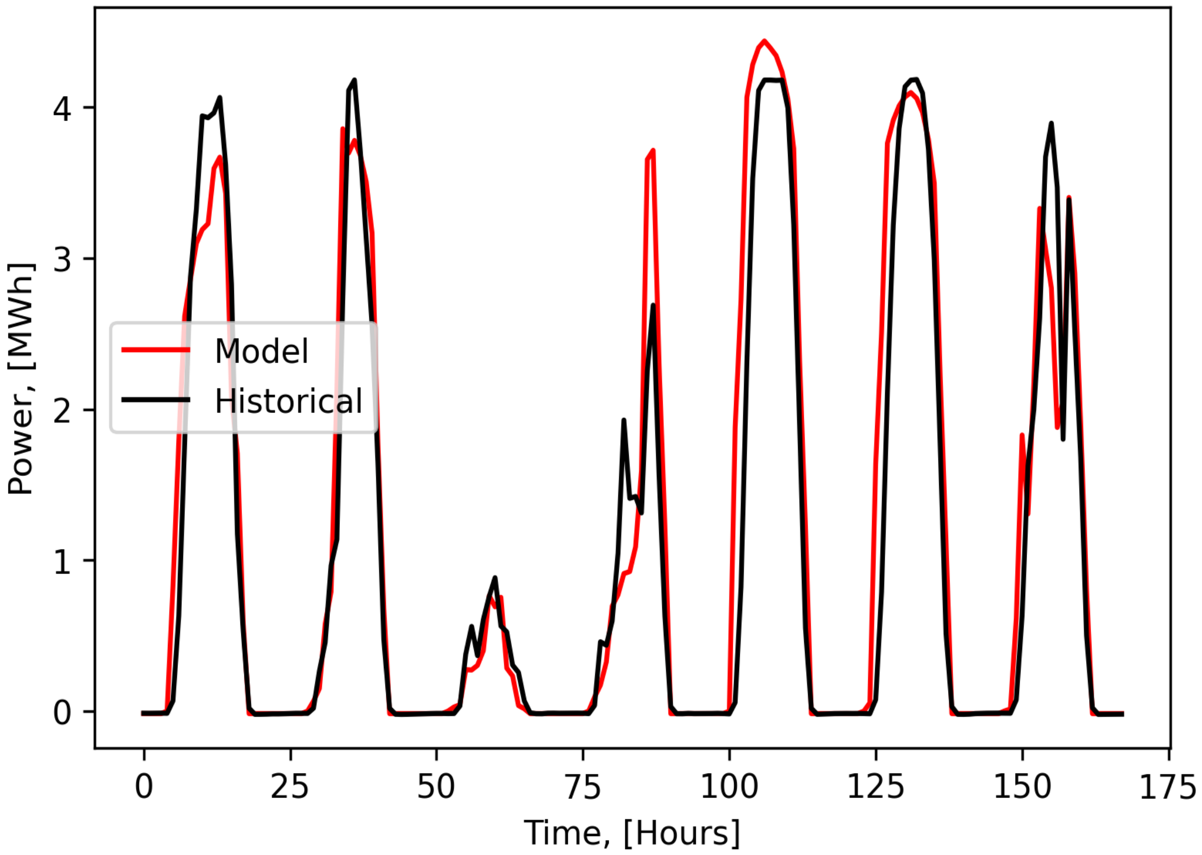


Microgrid Model



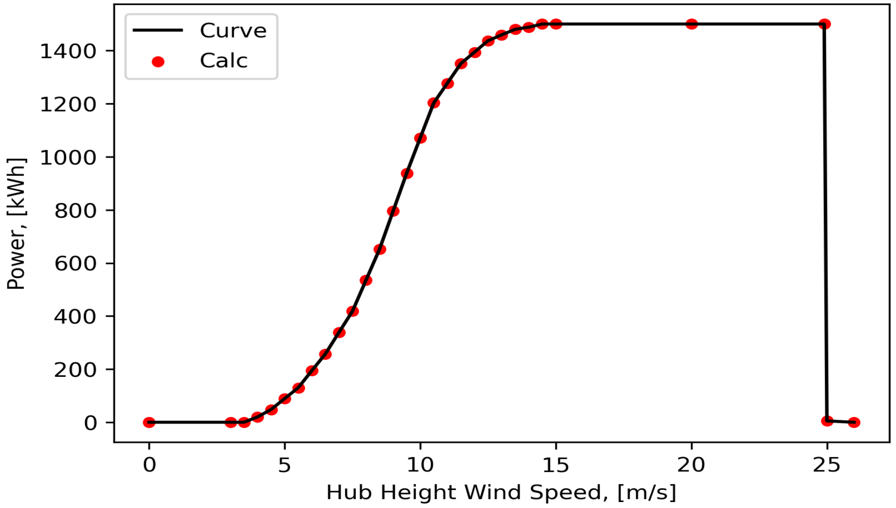
Modeling Renewables - Solar

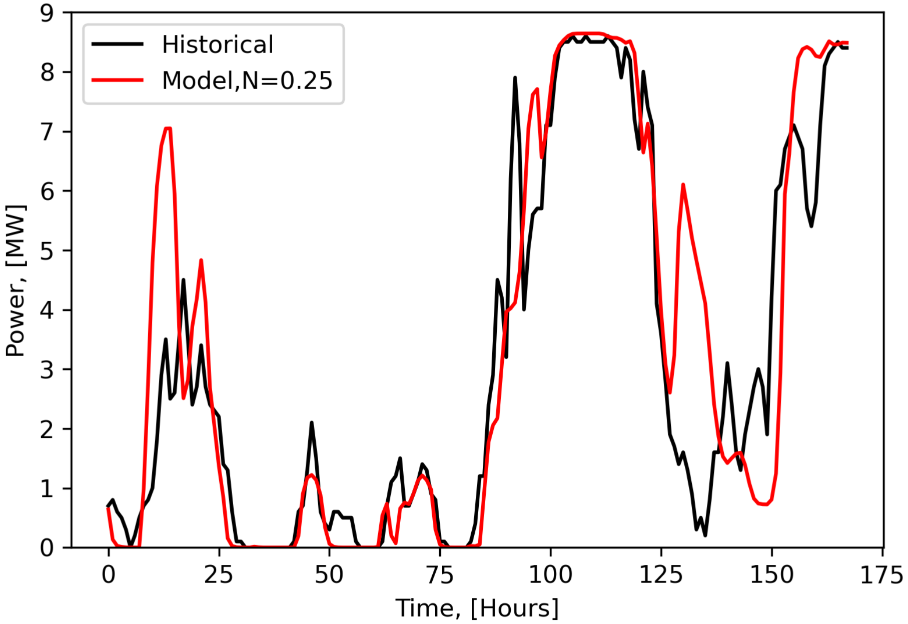
- Solar farm 1.0, 2.0
  - Fixed and East-West Tracking
  - 27,200 MWhr/yr
- Modeling parameters:
  i. Capacity (& rated intensity)
  ii. Latitude
  iii. North-South tilt
- Inputs
  i. Efficiency
  ii. Area
  iii. Transmissivity
  iv. Temperature Coefficient
  v. Day-of-year, Hour-of-day
  vi. Cell Temperature (based on climate data)
  vii. Direct Normal Intensity (DNI)
  viii. Diffused Horizontal Intensity (DHI)



Modeling Renewables - Wind

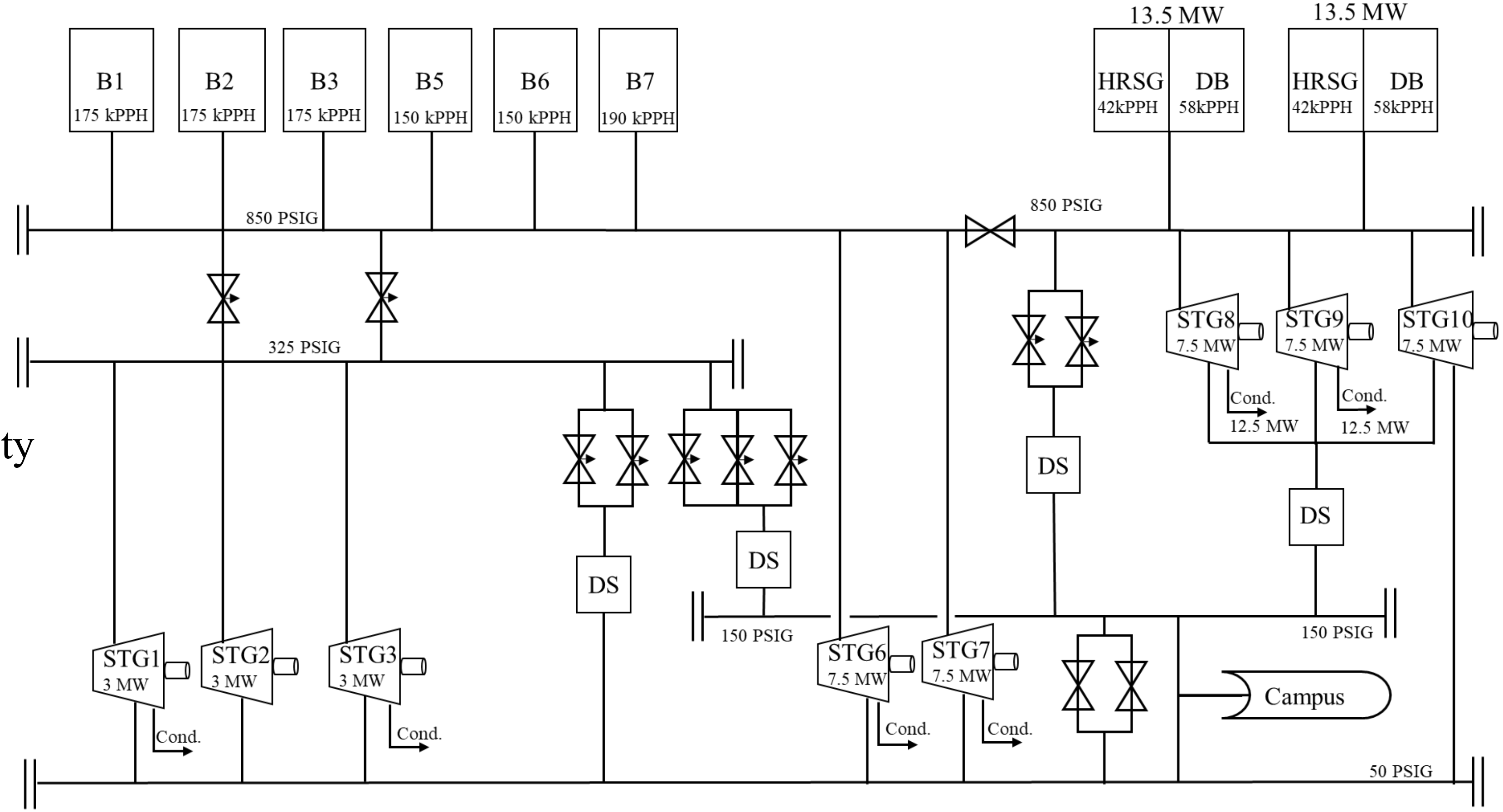
- Wind
  - PPA with Rail Splitter Wind farm
  - 8.6% of real-time generation
  - ~25,000 MWhr/yr
- Modeling parameters:
  1. Turbine power curve (from manufacturer)
  2. Wind speed correction (ground to hub height-power extrapolation)
- Inputs
  1. Number of turbines
  2. Turbine capacity
  3. Weather data (wind speed from NSRDB)





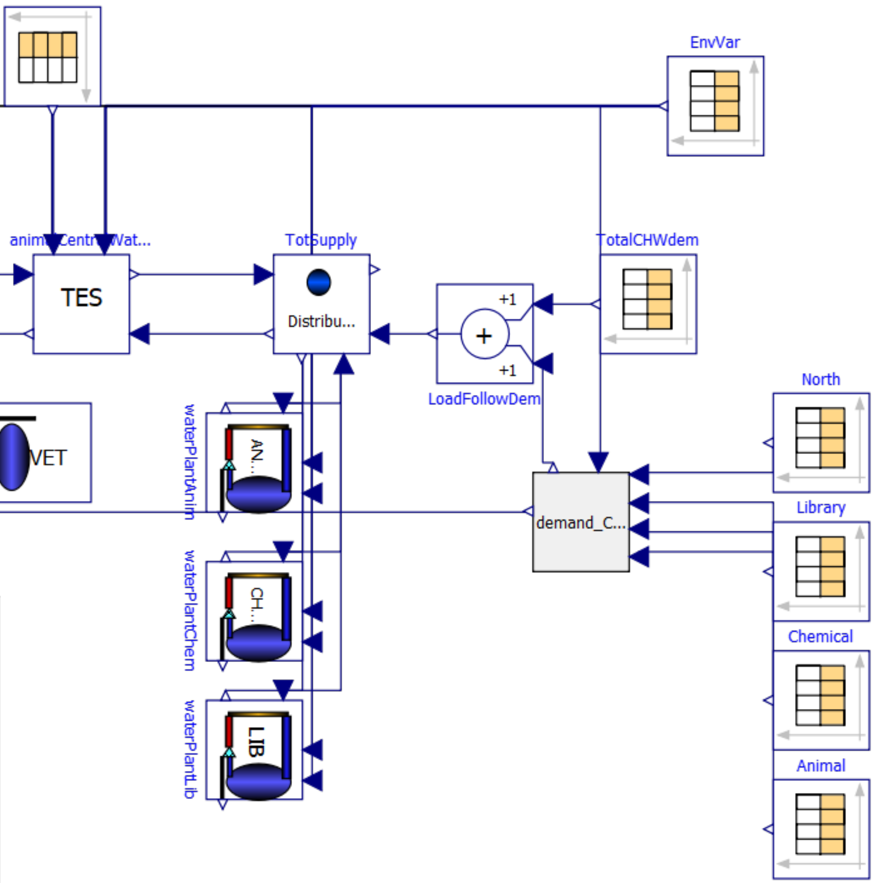
Modeling - Abbott Power Plant

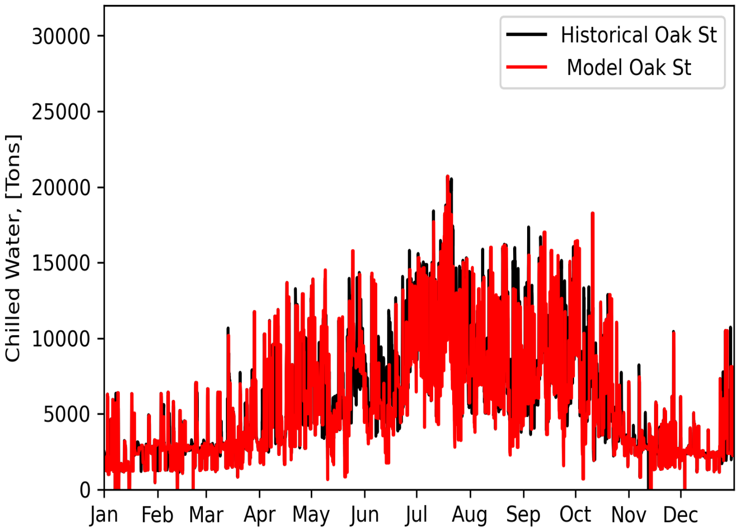
- Steam
  - 50MWth average demand
  - 150 and 50 psig
  - 100% of campus needs
- Electricity
  - ~45% of campus electricity
  - Biproduct of steam demand
  - CT provide base load to electricity demand (13.5 MWe each)
- Modeling parameters:
  i. Capacity
  ii. Ramp Rates
  iii. Cogeneration Ratio
- Inputs
  i. Electricity Demand
  ii. Steam Demand



Modeling – Chilled Water

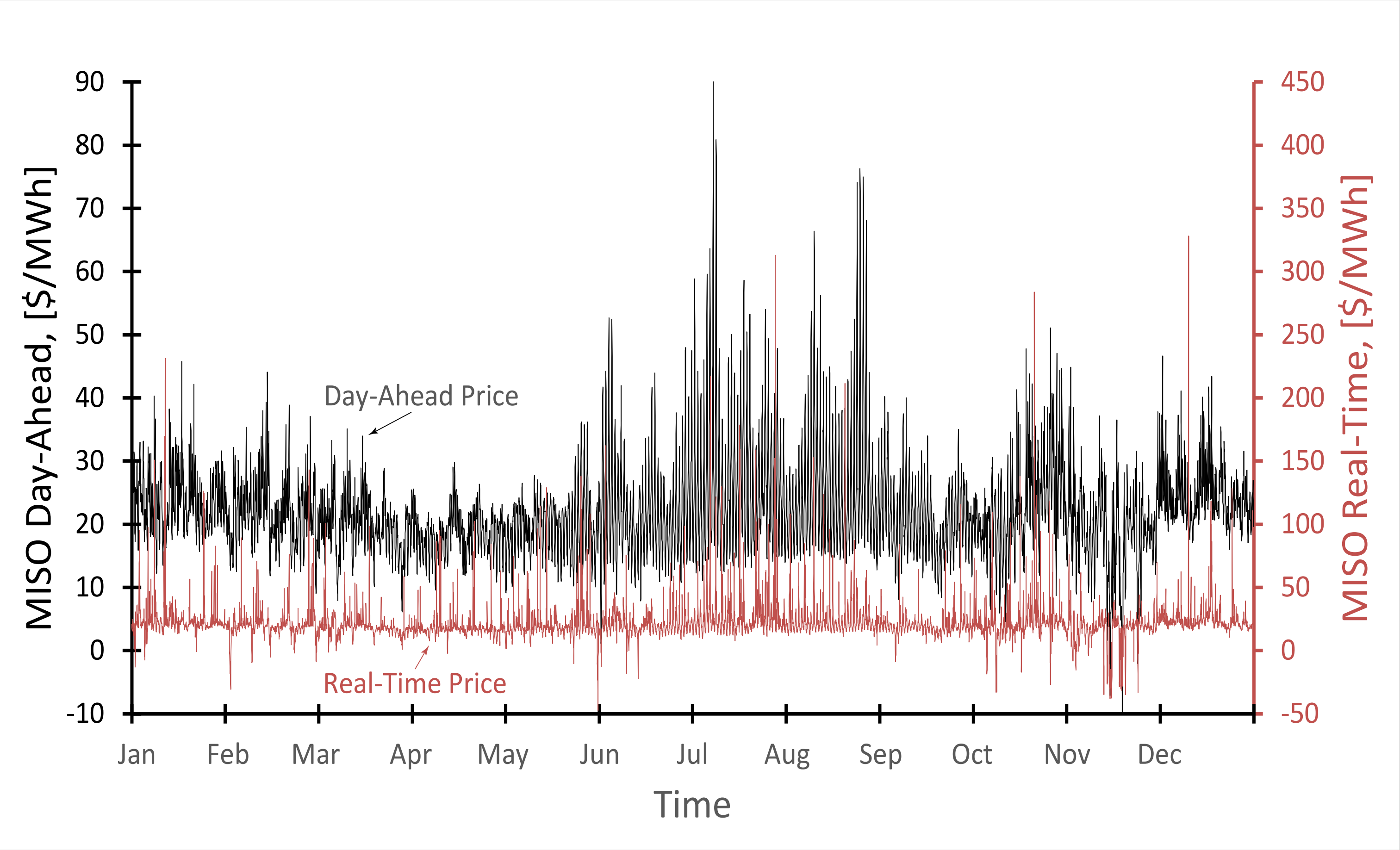
- 6 chiller plants (23 chillers)
  - Electricity (21)
  - High pressure steam (2)
  - Can operate using predicted load or historical load
- Thermal energy storage
  - 6.5 M gal storage capacity
- Modeling parameters:
  1. Capacity
  2. Ramp Rates
  3. Storage Capacity
  4. Day Ahead Economics (Arbitrage)
- Inputs
  1. Chilled Water Demand
  2. Environmental Data





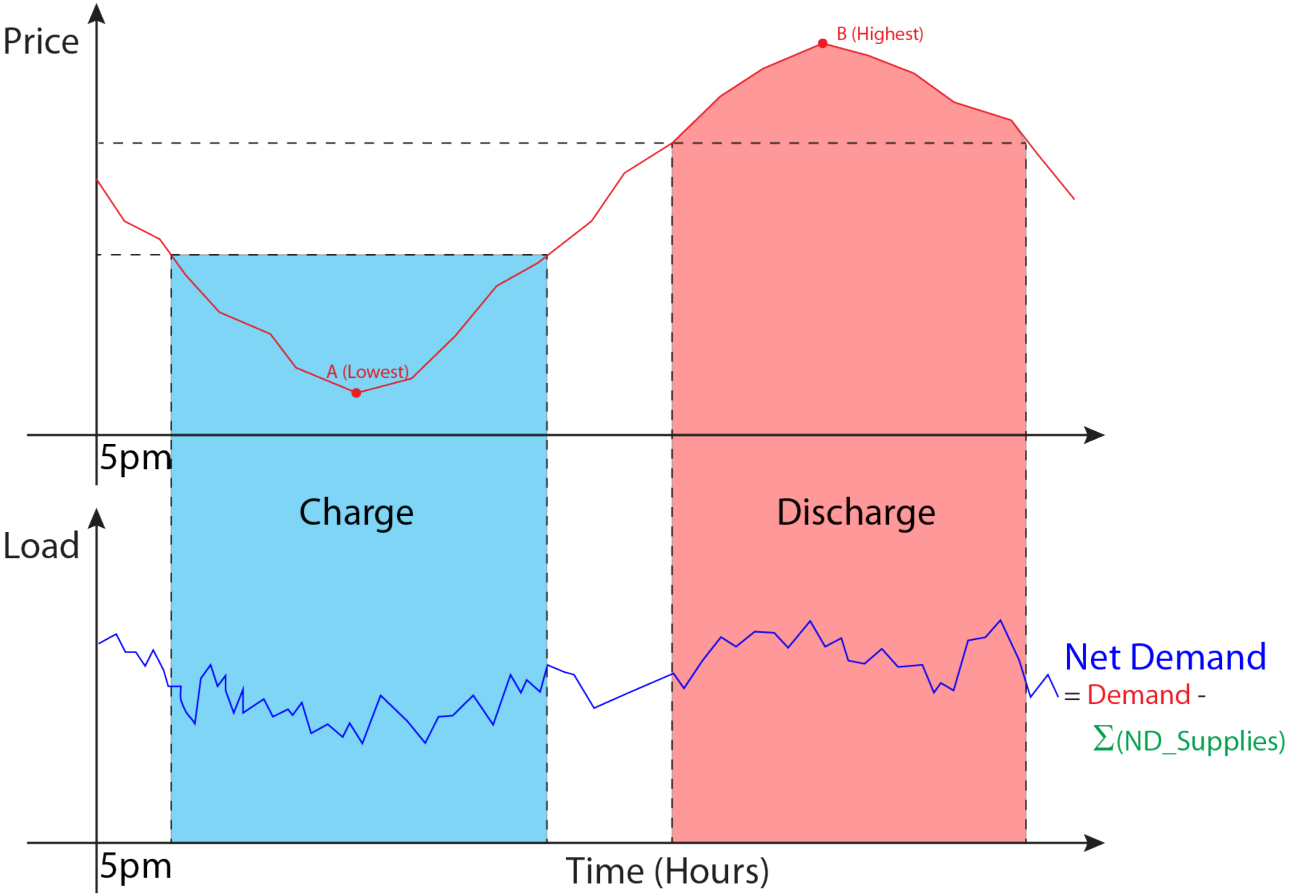
Modeling – Surrounding Grid

- Ameren (Miso)
- Utilization
  - Provides shortfall
  - Offload excess
- Pricing:
  - Real-time
  - Day-ahead
  - Futures (not currently implemented, or frequently used by F&S for electricity)



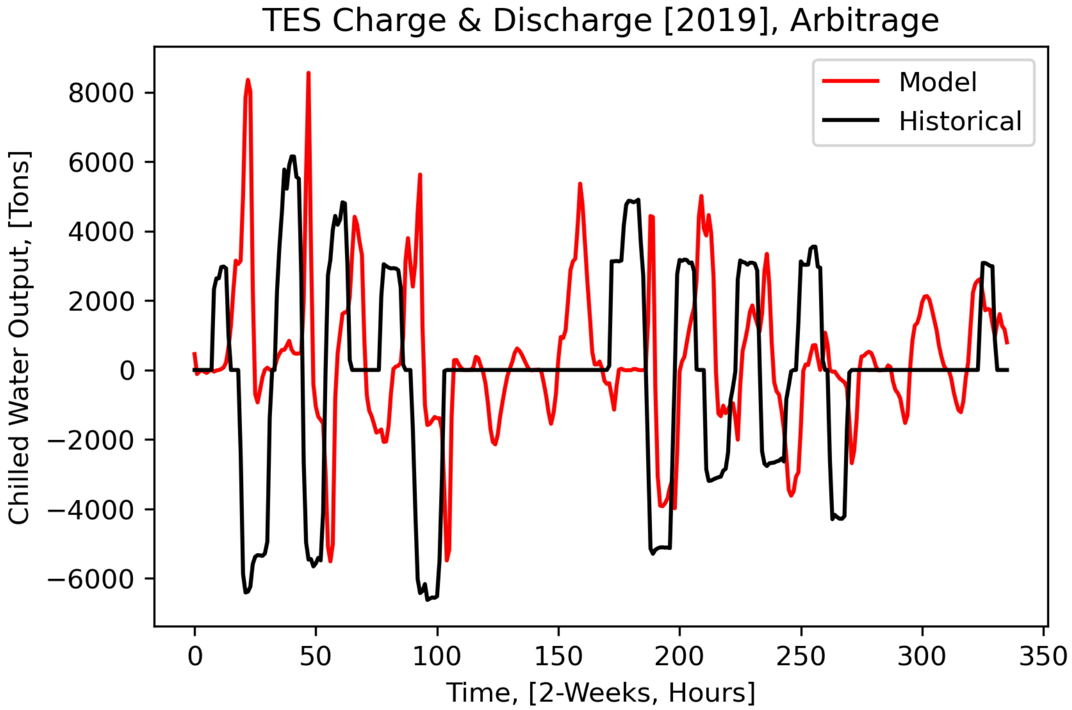
Arbitrage Method – DA Market

- Realistically, the tank aims to charge and discharge chilled water during the lowest and highest day ahead pricing respectively.
- Only charges when there is spare generation capacity
- Only discharge when there is campus demand.
- State of charge with storage tanks are tracked to prevent over charging or discharging



Modeling – Storage

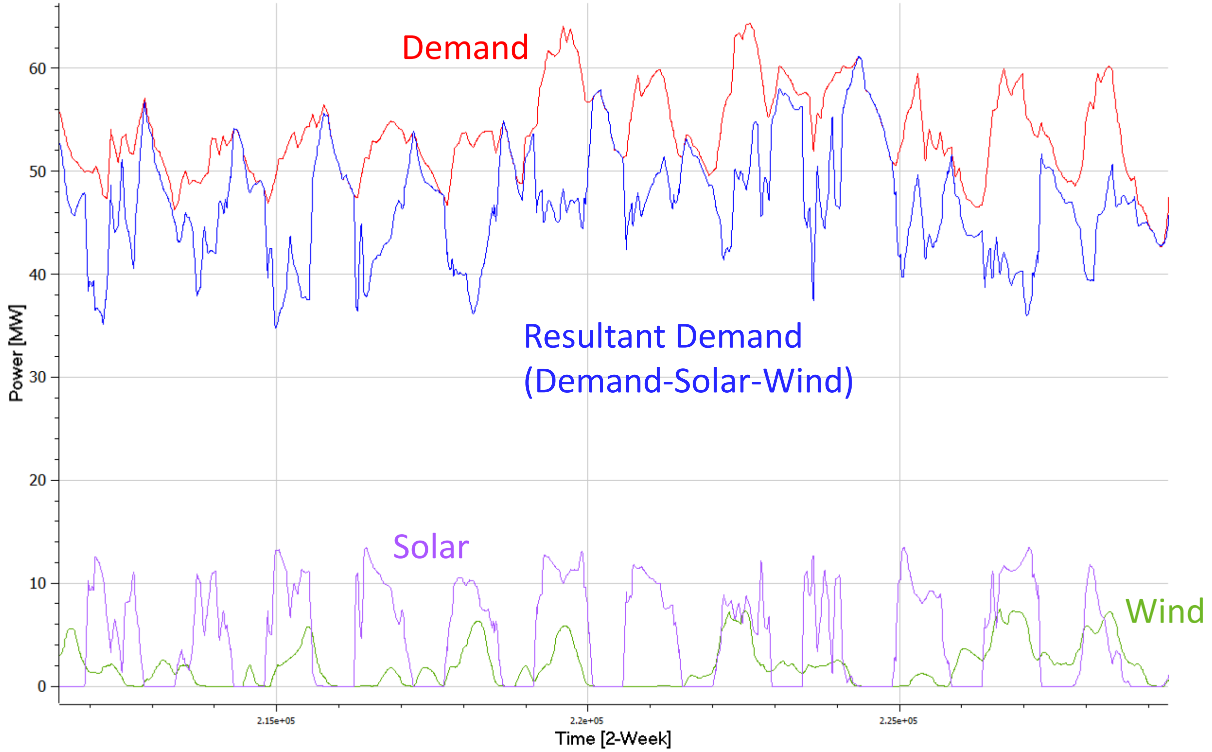
- Thermal storage
  - Chilled water
  - Molten salt
- Arbitrage - Uses day ahead pricing to forecast electricity demand to determine storage needs
- Actual TES operation considers more operational factors (maintenance, component cycling, demand forecasting, etc.)



	Charge TES (Tons)	CHW Discharge TES (Tons)	STD Charge	STD of Discharge
Historical	8,348,335	8,147,928	2,312	1,912
Model	7,221,480	7,148,775	1,724	1,756

Impact of Renewables

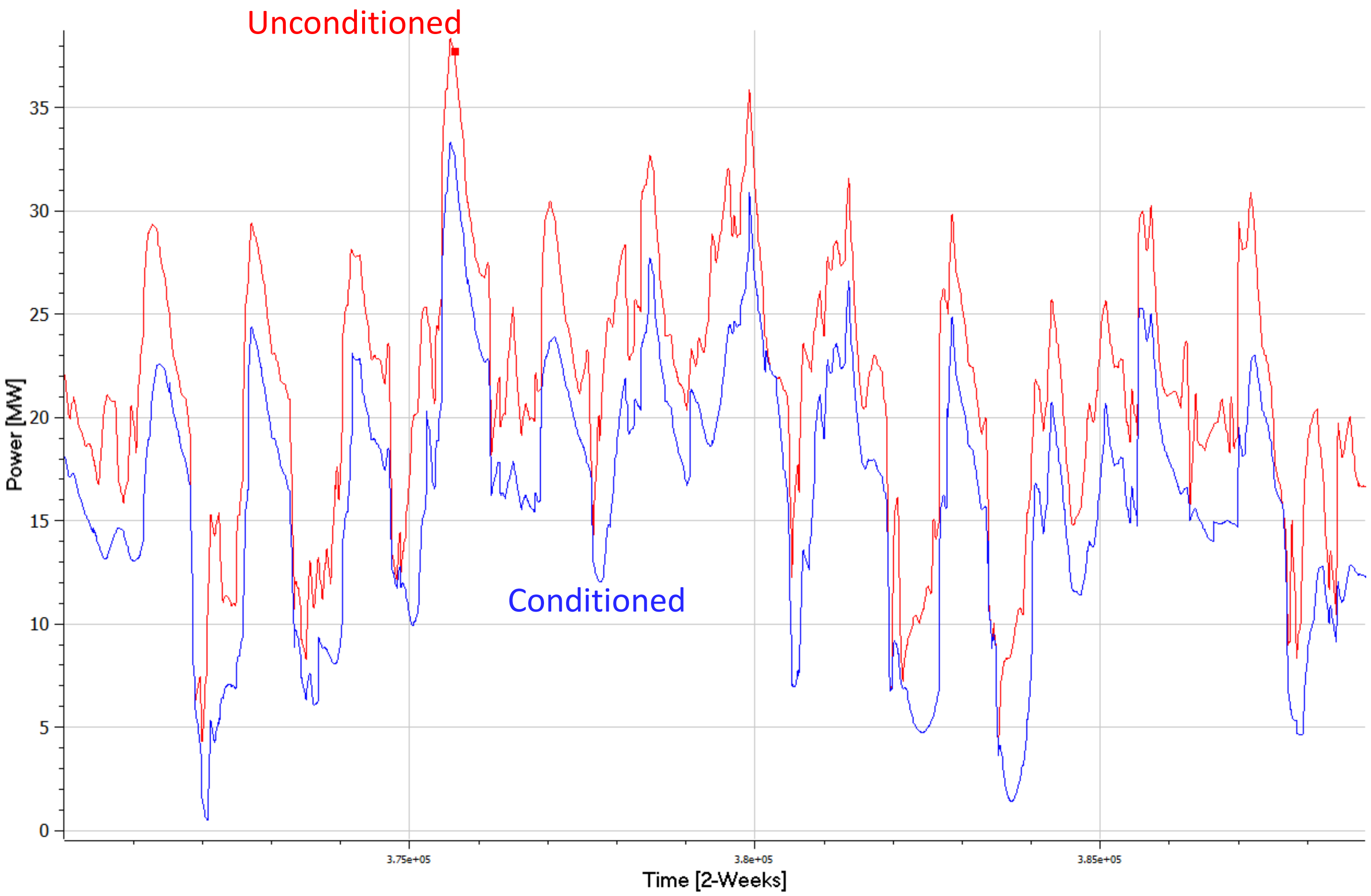
Renewables on Total Demand



Demand after Cogeneration Sources

Load Conditioning with Storage for 12 hours

- **5 + 5MWe = 5MWe reactor paired with 5WMe storage capacity**



Results with Various Configurations

Configuration	APP CO_2 (10^3 tonnes)	Electric Import CO_2 (10^3 tonnes)	Net CO_2 (10^3 tonnes)	APP Power Produced (GWhr)	Power Imported (GWhr)	Electric Import Cost ($M)	Fossil Fuel Cost ($M)	Summed Cost ($M)
1) Base	205.86	59.81	265.67	306.30	88.10	4.44	11.13	15.57
2) B-CT	115.96	220.38	336.33	69.79	324.61	16.11	6.27	22.38
3) 15 MW_{th}	185.61	54.59	240.20	313.98	80.41	4.06	10.04	14.10
4) 5 MW_e	205.86	30.08	235.94	350.09	44.31	2.51	11.13	13.64
5) 5+5 MW_e	205.86	35.89	241.75	341.53	52.87	2.67	11.13	13.80
6) 90 MW_{th}	151.41	-26.63	124.77	433.63	-39.23	-0.71	8.19	7.48
7) 30 MW_e	205.75	-118.46	87.29	568.89	-174.49	-4.40	11.13	6.73
8) 30+30 MW_e	205.86	-3.27	202.59	399.21	-4.81	-0.14	11.13	10.99

*Fossil fuel costs represents the total annual cost generated by natural gas, coal, and fuel oil usage on-campus

**Electric import cost represents the total annual cost due to purchased electricity outside the grid excluding renewable sources (Rail Splitter)

Note: Config (4 &7) generate fixed electricity, Config(3 &6) retrofitted thermal output, Config(5 &8) use load conditioning

Results for Optimizing MSS & Microreactor for electricity

Case	Ameren Power Imported (GWhr)	Untapped Reactor Power (GWhr)	Ameren Cost ($M)	Fuel Cost ($M)	Total Cost ($M)	Hours Without Import/ Export
Base	88.1	0	4.44	11.13	15.57	2
5+5*12h	52.86	8.5	2.67	11.13	13.8	1614
5+5*24h	53.14	8.72	2.68	11.13	13.82	1106
5+5*24h_LF	52.86	8.44	2.66	11.13	13.8	1518
5+10*12h_LF	49.51	5.08	2.51	11.13	13.65	2577
10+10*12h	27.93	27.31	1.43	11.13	12.56	2113
10+10*24h	28.02	27.28	1.44	11.13	12.57	2252
10+10*24h_LF	27.98	27.24	1.43	11.13	12.56	3224
10+20*12h_LF	21.58	20.84	1.14	11.13	12.27	4881
15+15*12h	11.6	54.71	0.64	11.13	11.77	4946
15+15*24h	11.3	54.24	0.62	11.13	11.76	4947
15+15*24h_LF	11.6	54.54	0.64	11.13	11.77	4838
15+30*12h_LF	4.32	47.26	0.3	11.13	11.43	6475

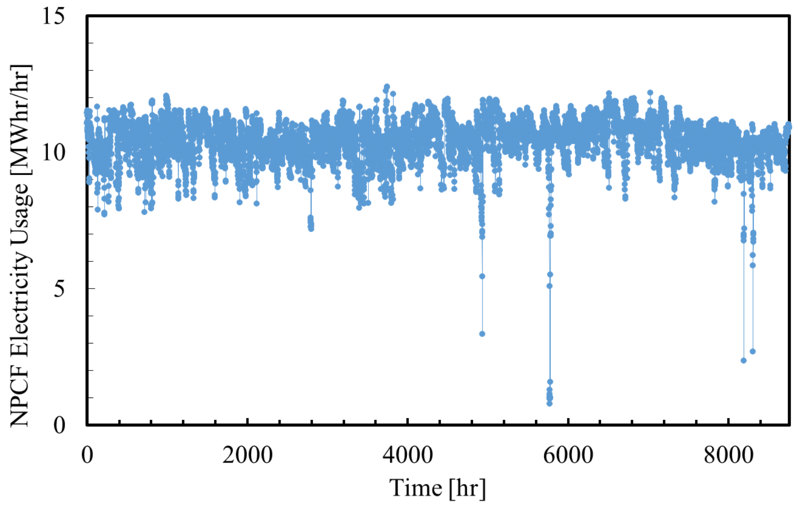
*Ameren cost generated from real time pricing

*Ex) 5+5*12h = 5MW reactor, 5 MW MSS with 12 hours of storage under load conditioning (LF represents load following)

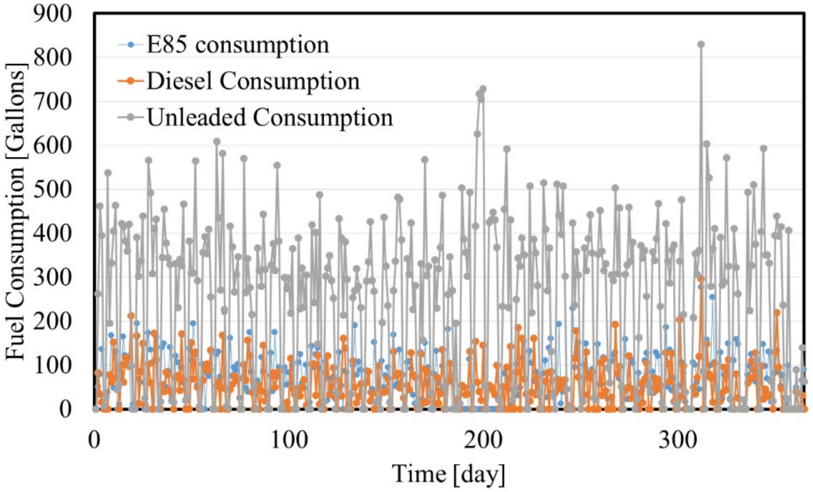
*Ameren Import is summed purchased and sold electricity to the grid,

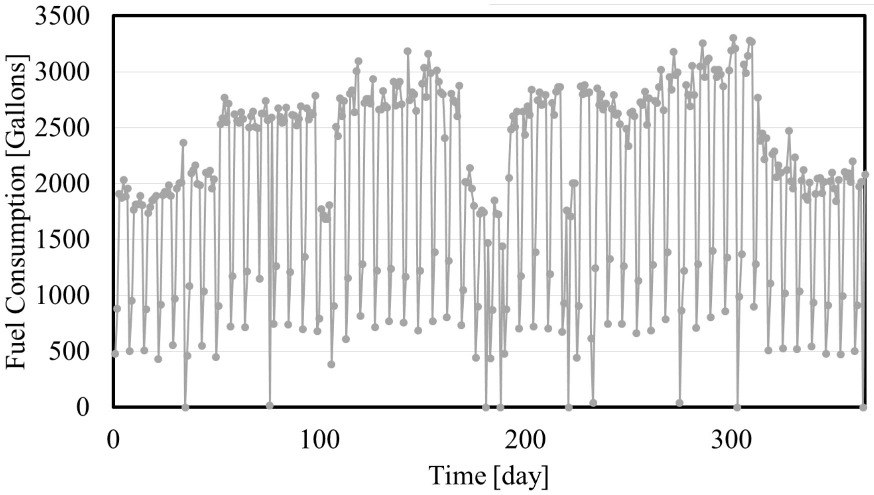
* 8760 Hours in a year

Work Direction



1. Modeling microreactors
2. High performance computing (electric and chilled water)
3. Hospital (data from UIC hospital)
4. Expand campus infrastructure to consider Hydrogen production for transportation needs





5. Application to potential markets.