DOE-NE Microreactor Program

Global Market Analysis of Microreactors

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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".

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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*

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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

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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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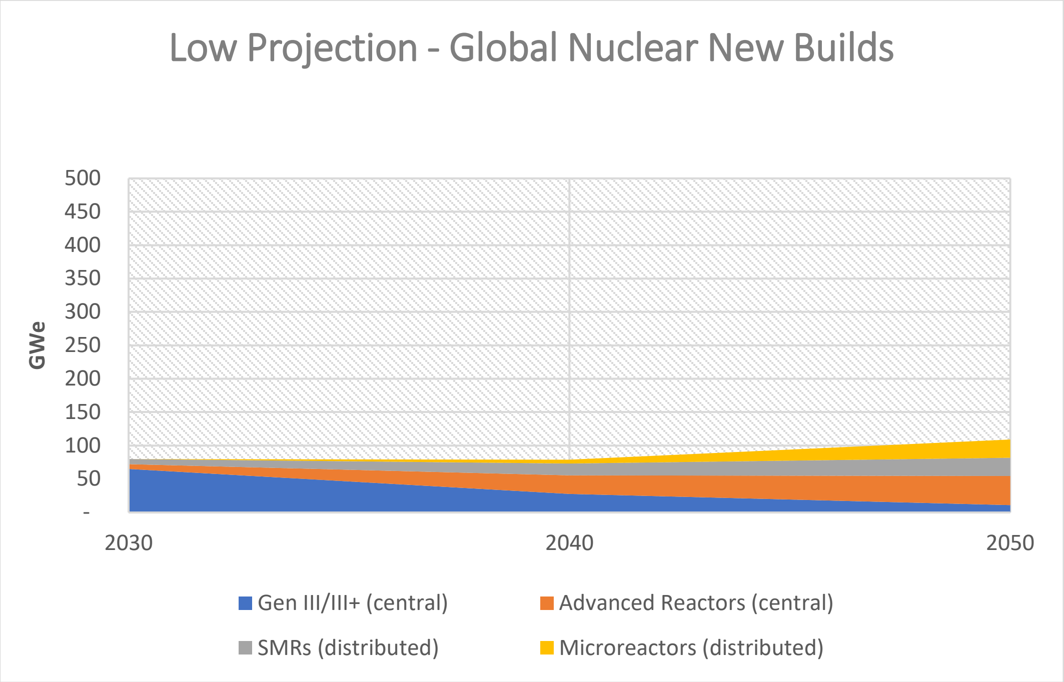
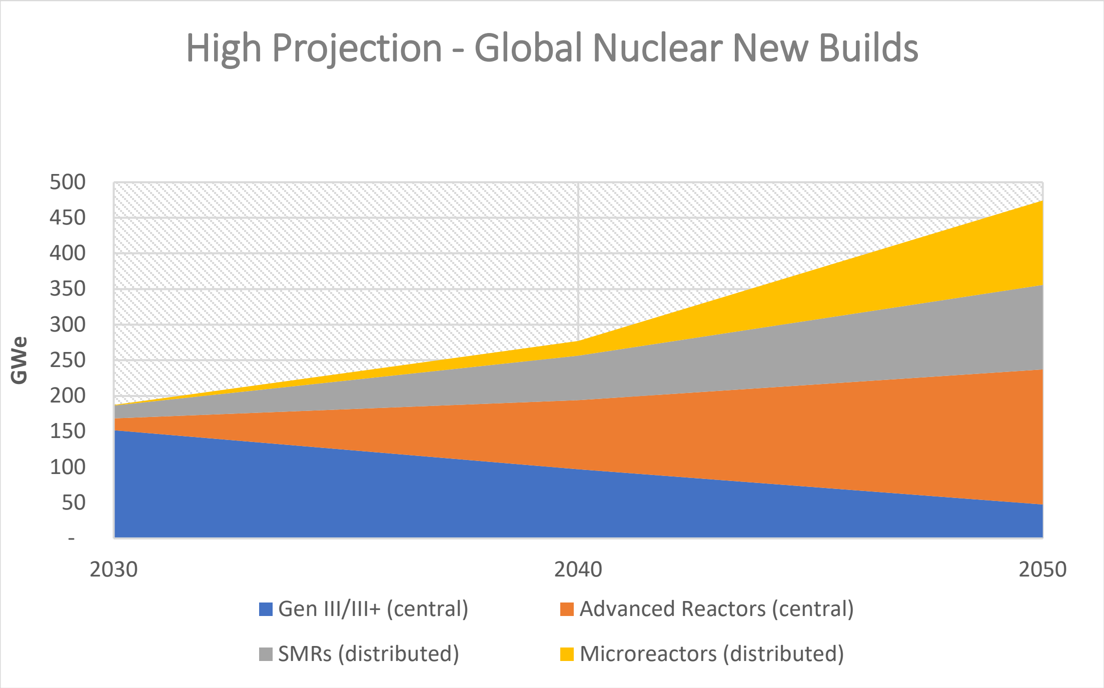
Microreactors were carved out of Global Nuclear Projections





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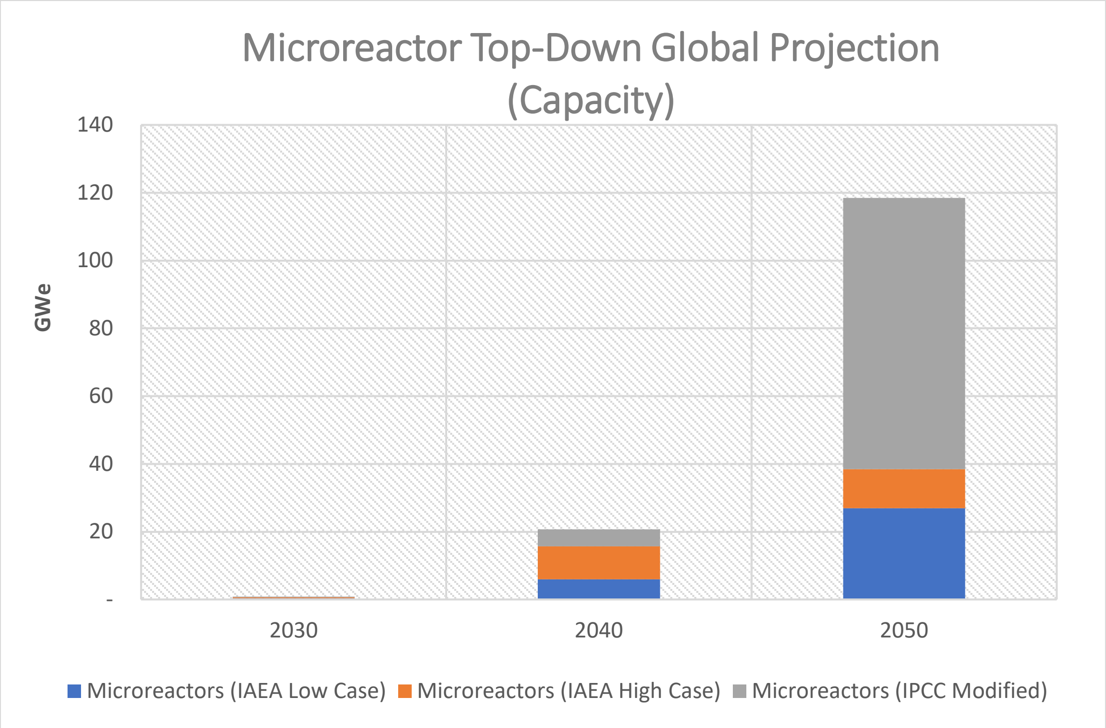
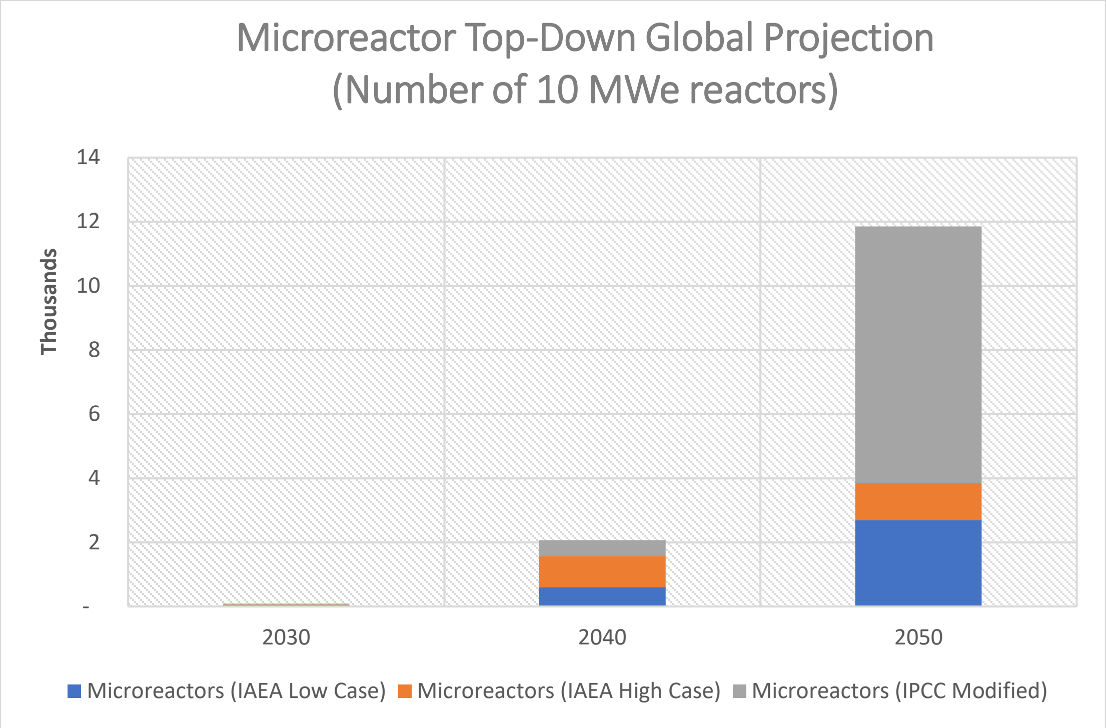
Microreactor Top-Down Global Projections





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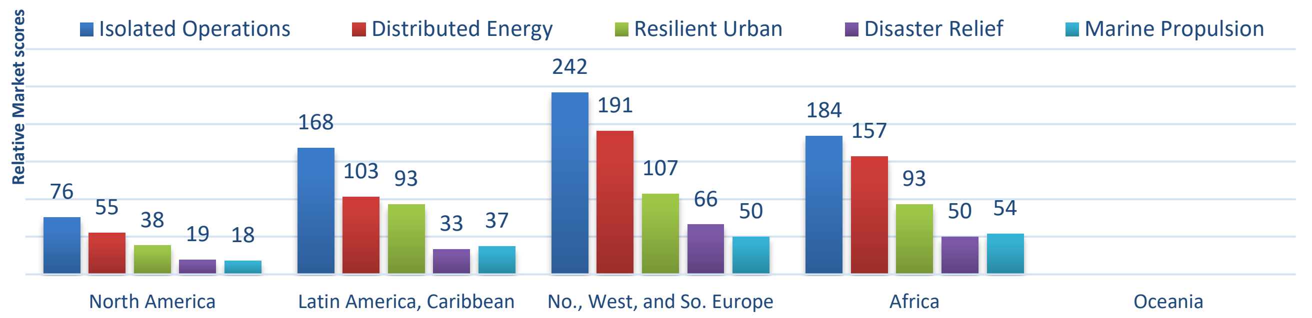
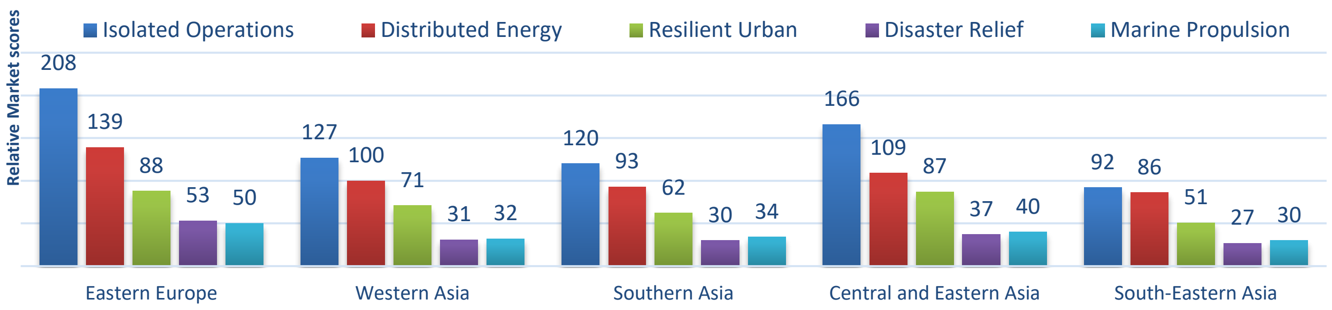
Results: Microreactor have potential to invigorate nuclear demand in existing markets and in developing economies

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.

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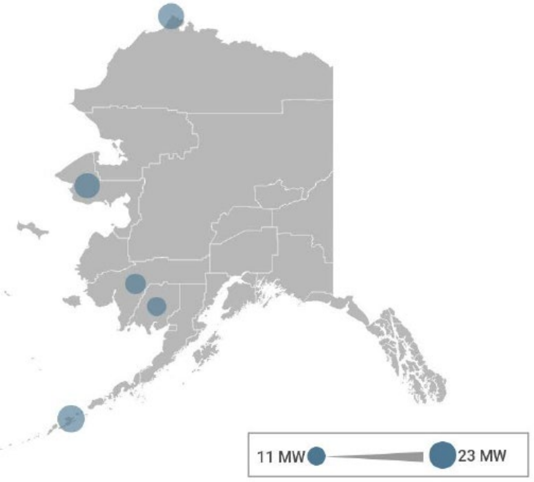
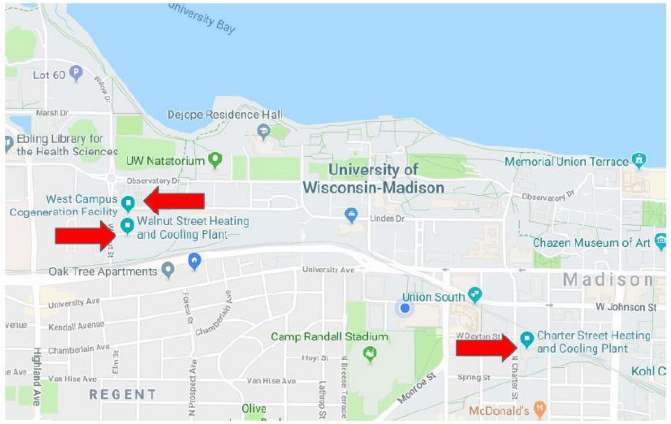
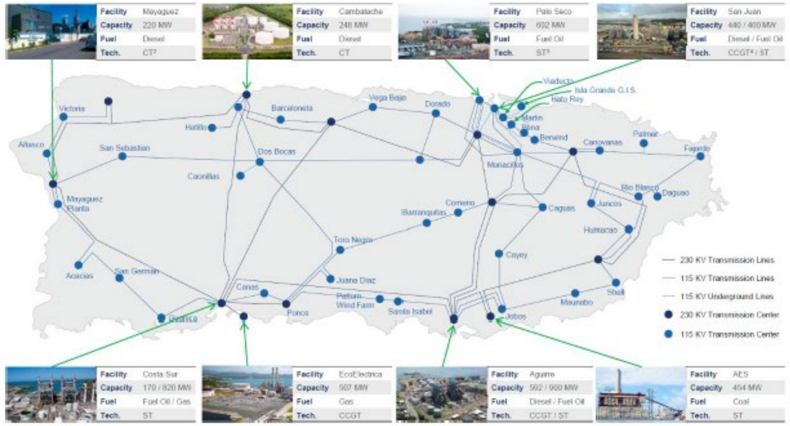
Microreactor Economic Analysis - Overview

- <u>Scope overview</u>. This work supports the understanding of the market and economic potential for microreactors in the U.S. and internationally.
- <u>Why</u>? Economic Performance and Market Analysis provides a techno-economic basis for support to industrial microreactor deployment and operation.
- <u>How</u>? 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:
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- 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.

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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.).

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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

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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.

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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.

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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.

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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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