NEI | REPORT

Cost Competitiveness of Micro-Reactors for Remote Markets

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Acknowledgements

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NEI Project Lead: Marcus Nichol, Director New Reactor Deployment, mrn@nei.org

NEI Project Support: Harsh Desai, Manager Energy and Economic Analysis, hsd@nei.org

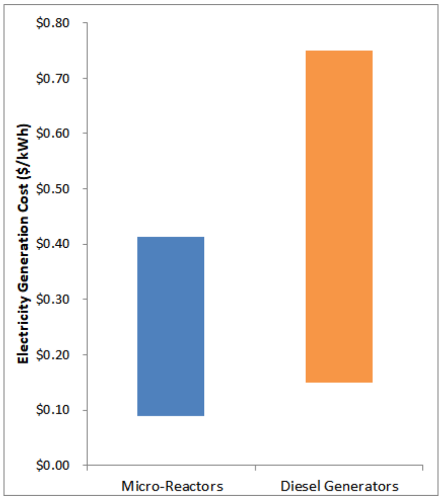
Notice

This document has been prepared by NEI to highlight the general cost and market competitiveness of stationary micro-reactors in the United States. This report does not consider the use of mobile micro-reactors. Neither NEI nor any of its employees, members, supporting organizations, contractors, or consultants makes any warranty concerning the document, guarantees its accuracy or completeness, assumes any liability for damages resulting from any use of information in this report, or warrants that such may not infringe privately owned rights.

Executive Summary

Micro-reactors are very small nuclear reactors capable of operating independently from the electric grid to supply highly resilient power, and are well suited to serve the power needs for several markets that currently do not have access to clean, reliable, resilient and affordable energy. This report assesses the cost competitiveness of stationary micro-reactors for use at enduring locations, and does not include consideration of mobile micro-reactors for shorter duration operations.

Micro-reactors can be cost competitive for remote applications such as arctic communities, islands, mines, and defense installations. We estimate the cost to generate electricity from the first micro-reactor will be between $0.14/kWh and $0.41/kWh. As companies continue to produce micro-reactors, future costs are estimated to fall to between $0.09/kWh and $0.33/kWh. The range of costs are due to variations in transport accessibility, site conditions, the technology, the ability to reduce future costs through lessons learned and the type of owner, i.e., private or public. Diesel generators, which are the primary source of electricity in many remote markets, are estimated to generate electricity at costs between $0.15/kWh and $0.60/kWh. The diesel generation costs are primarily driven by the cost of fuel and the cost to transport the fuel to remote locations.



Micro-reactors provide a combination of benefits not provided by other energy sources—they are highly resilient, carbon-free, flexible, and can produce electricity on demand and can operate for years without the need to refuel. In comparison, diesel generators rely on an off-site supply and on-site storage of large amounts of diesel fuel, the delivery of diesel fuel is subject to weather-related interruptions, and they also emit carbon dioxide, particulate matter, and other air pollutants.

> *Micro-reactor technology is maturing rapidly, with over a dozen designs under development, and an expected deployment of the first commercial micro-reactor in the mid-2020s.*

Customer interest is rapidly growing as they recognize the potential value that micro-reactors offer to meet their energy needs. We expect the small size and potential to produce a large number of micro-reactors will rapidly reduce costs and accelerate deployment of future micro-reactors.

Further enhancements to Federal Power Purchase Agreement authorities, DOE supply of high-assay low-enriched uranium, and the use of reactor demonstrations, which are addressed in the Nuclear Energy Leadership Act introduced by Senator Murkowski and others in March 2019, could significantly accelerate the deployment and reduce the costs of micro-reactors.

Table of Contents

Figures

1 INTRODUCTION

Micro-reactors are an emerging nuclear energy technology that are well suited to address energy needs in a number of markets, and customer interest in this innovative technology is growing rapidly. Micro-reactors are very small nuclear reactors, typically in the 1 MWe to 10 MWe range with some designs being even smaller or slightly larger. This is 100 to 1,000 times smaller than a standard reactor on the grid. Micro-reactors are capable of operating independently from the electric grid to supply highly resilient power for critical loads under normal and emergency conditions.

This report only focuses on stationary micro-reactors and does not assess the economics of mobile micro-reactors which are discussed in a separate report published by the U.S. Army.[1] Stationary micro-reactors are intended to operate at the same location for many years or even decades. Mobile micro-reactors are intended to operate at a location for shorter durations and include features that allow them to be set up or removed in a few days.

This report assesses the costs and competitiveness for the deployment of stationary micro-reactors in the United States. Micro-reactors are a key nuclear energy technology for the future and will complement two other nuclear energy product categories: the large 1,000+ MWe nuclear reactors, and the small modular reactors that are less than 300 MWe. Today, nuclear energy provides about 20% of the electricity in the U.S. and accounts for nearly 60% of the electricity from zero-carbon emitting sources.

This report is intended to inform potential customers of micro-reactors and stakeholders, including remote communities, mines, and defense installations. This report is also intended to inform the U.S. Department of Defense's (DoD) investigations on the use of micro-reactors deployed at enduring locations to provide highly resilient power to mission critical defense installations, enabling them to operate independent of the electricity grid.

The 2019 National Defense Authorization Act (NDAA) Section 327 requires the Secretary of Energy to develop a report to describe the requirements for and components of a pilot program using micro-reactors to provide resilience for critical national security infrastructure at DoD facilities. The pilot program would contract with a commercial entity to site, construct and operate micro-reactors of no greater than 50 MWe per reactor, to provide resilience for national security infrastructure at DoD and DOE facilities, by December 31, 2027. An earlier Nuclear Energy Institute report established a roadmap for the deployment of a micro-reactor at a domestic defense installation.[2] That report provides a timeline and recommends actions that support the deployment a micro-reactor in the mid-2020s.

[1] Army Study on the Use of Mobile Nuclear Power Plants for Ground Operations
[2] NEI Roadmap for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations

2 MICRO-REACTOR BENEFITS

Micro-reactors, like other nuclear energy technologies, offer a combination of benefits that are not found all together in other energy sources.

Highly Resilient and Reliable – Micro-reactors can operate 24 hours a day, 7 days a week, 365 days a year, and most can operate for 10 years or more without the need for an off-site supply of fuel. Micro-reactors are being designed to protect against severe natural phenomena as well as man-made physical and cyber security threats, and many are being designed with the ability to operate in island-mode and include black-start capabilities, which means they can initiate recovery from a blackout. Micro-reactors are expected to be able to operate at a capacity factor of 95% or more.

Clean and Environmentally Friendly – Micro-reactors are a nuclear energy technology and therefore do not emit greenhouse gases or "criteria" pollutants.[3] Nuclear energy has one of the lowest total carbon footprints of any energy source, roughly the same as hydroelectric and wind.[4] DoD estimates that the land required to provide a critical load of 1 MWe would be 53 m^2 (0.01 acre) for diesel generators and 10,000 m^2 (2.47 acres) for solar PV and storage.[5] Others have estimated that wind and solar would require 70.6 or 43.5 acres of land, respectively, for each megawatt produced.[6] Scaled to 20 MWe, diesel generators would require 0.26 acre to serve a 20 MWe load and solar PV with storage would require 49 acres. Micro-reactors are expected to require less than 0.1 acre to serve a load of 20 MWe.[7]

Flexible and On-Demand Operations – Micro-reactors can produce power on-demand and operate independent of weather conditions. Micro-reactors can vary their power output to match changes in demand. This attribute makes micro-reactors suitable to serve changing loads and compatible with intermittent sources of energy like renewables. Micro-reactors that are needed to vary electrical output can alternate between the generation of electricity and heat, or utilize battery storage to optimize the capacity factor and economics.

Electricity and Heat – Micro-reactors which offer high reactor outlet temperatures can produce both electricity and heat, or can be used exclusively to provide heat. Heat can be used for industrial applications such as oil refining and chemical processing. In colder climates, heat can be used for district heating of homes and businesses. The electricity or high-temperature heat from a micro-reactor can also be used to desalinate and purify water, and to generate hydrogen. The use of heat for industrial processes or district heating can improve the utilization of the micro-reactor in areas with variable demand for electricity, thus improving the market demand for micro-reactors. However, the study of the economics of micro-reactor heat is beyond the scope of this report.

Simple and Safe – Micro-reactors designs are simple to operate due to their small size, inherent level of safety and security, and the incorporation of advancements in technology, such as improved materials and high fidelity computer modelling. Many designs operate automatically, requiring very few human actions. Micro-reactors are similar to research reactors in their size and risk, which have a long history of safely operating on university campuses located in population centers.

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[3] U.S. EPA Criteria Air Pollutants
[4] WNA Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources
[5] DoD Resilient Technology Comparison
[6] Strata The Footprint of Energy: Land Use of U.S. Electricity Production
[7] Land use reported by Westinghouse for eVinci. Some designs fit inside an ISO Container.

3 MARKET OPPORTUNITIES

Micro-reactors are well suited to serve the power needs for several markets that currently do not have access to clean, reliable, resilient and affordable energy. Many of these markets are in remote areas, such as arctic communities and mining operations. However, micro-reactors are also an option to power secure micro-grids for critical infrastructure such as defense installations and emergency response facilities.

3.1 Remote Communities

In Alaska, diesel and coal account for roughly 15% and 6% of the electricity generation, respectively. Communities in some regions of Alaska, notably the interior and the west, are almost wholly dependent on diesel fuel to generate electricity, while coal is a prevalent source of energy near Fairbanks and other parts of the northern Railbelt.[8] The lack of access to clean, affordable and reliable electricity negatively impacts the livelihood of these communities. Even in regions that receive most of their power from natural gas or hydro, diesel generators can produce a significant portion of the electricity or are otherwise required for back-up.[9]

Alaska has about 300 remote communities that have small electric grids and are not linked with other communities through large interconnected grids, increasing the importance of having access to a highly reliable and resilient source of energy. Residents in nearly 200 of these remote communities depend on economic assistance from the state's Power Cost Equalization program (PCE) to subsidize their power costs.[10]

These communities are highly dependent upon diesel generators to provide electricity which have high generation costs and are vulnerable to disruptions in the supply of diesel fuel. Electricity prices in these remote communities ranged from $0.41/kWh in Nome, AK to $1.02/kWh in Takotna, AK in 2014, which is up to 16 times the electricity cost in the rest of the U.S. Some households in these communities spend up to 47% of their total income on energy.[11,12,13]

In FY2018, the State of Alaska appropriated $32.1 million for the PCE program, based on a PCE base rate of $0.1758/kWh, which is roughly the price in Anchorage, Fairbanks and Juneau. Using micro-reactors to bring affordable electricity to remote communities at costs near or below the base rate could eliminate the need for the PCE subsidy and lower the energy costs for these communities. Using micro-reactors can also improve energy security by eliminating dependence on fuel deliveries that can be affected by weather, ice conditions, and river water levels. The price of electricity in areas with larger grids ranged from $0.10/kWh in Ketchikan, which relies primarily on hydroelectric generation, $0.14/kWh in Anchorage where natural gas is prevalent, and $0.23/kWh in Fairbanks, where diesel and coal are the primary fuels. However, many of these areas face challenges due to limited interconnections, aging generation infrastructure, and significant reliance on fossil fuels.

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[8] The Alaska Railbelt is the region from extending from Fairbanks to Anchorage and the Kenai Peninsula. The Railbelt is home to over 60% of the State's population and the State's largest electricity transmission system.
[9] Alaska Energy Statistics 1960-2011, Prepared December 2013
[10] Alaska Energy Authority Power Cost Equalization
[11] Third Way Solving Energy Challenges in Remote Communities
[12] U.S. Energy Information Administration State Profile
[13] Commonwealth North Energy for a Sustainable Alaska: The Rural Conundrum

Island communities typically have higher electricity prices with smaller, less reliable electricity grids. Islands such as Hawaii, Puerto Rico and Guam all have electricity prices that are much higher than the continental U.S., ranging from roughly $0.20/kWh to $0.40/kWh. The reliance on the importation of diesel, natural gas and coal to generate electricity in these communities contributes to higher prices and reduced energy security. In 2017, hurricanes Maria and Irma destroyed the second largest wind and solar farms in Puerto Rico and damaged most of the other solar and wind generation on the island.

Petroleum supplies almost half and natural gas supplies nearly one-third of Puerto Rico's electricity, with many of these power plants being 28 years older than the U.S. average and experiencing outage rates 12 times the U.S. average. Puerto Rico's largest generating plants are in the south, far from the population centers in the north. Locating micro-reactors in the north, which are capable of being safely located near the population centers, could dramatically increase the resilience and reliability of the island's electricity system.

In Hawaii, diesel generators supply about two-thirds of the electricity demand, contributing to the highest electricity prices in the U.S. Hawaii is also characterized with isolated island grids, increasing the need for local energy sources to be highly reliable and resilient.

Guam's electricity is produced primarily from diesel fuel, and electricity prices are two to three times higher than in the 50 states. Guam hosts the U.S. Naval Base Guam and Anderson Air Force Base.[14]

3.2 Mining Operations

Mining operations are often times located in remote areas without access to reliable electricity from the grid. Power is typically a large portion of the operating costs, and a loss of power can have significant financial impacts on the mining operations. The cost of electricity for remote mining operations is typically between $0.20/kWh and $0.50/kWh.[15,16]

The life of a mine can vary depending on the type, quality and abundance of the target ore. While some mines could have a lifetime of only a few years, gold mines have an average life of 10 to 20 years, and some copper mines can operate for 70 years.[17,18] Interestingly, lower power costs from a micro-reactor could help extend the life of the mine by making lower grade ore more profitable.[19]

3.3 Defense Installations

DoD manages over 500 fixed installations, which includes activities of the U.S. Air Force, Army, Navy, Marine Corps, and numerous Defense Agencies. DoD is the single largest energy consumer in the U.S., with installation energy accounting for 21% of the total Federal energy consumption. In FY2016, DoD installations used 201,410 billion British thermal units (Btu), costing approximately $3.7 billion. Overall

[14] U.S. Energy Information Administration State Profiles for Hawaii, Puerto Rico and Guam
[15] THEnergy Solar-Diesel-Hybrid Power Plants at Mines: Opportunities for External Investors
[16] THEnergy Low-Load Gensets for Solar-Diesel Hybrid Plants in the Mining Industry
[17] Statista Duration of the Extraction Period of a Mine, by Selected Commodities
[18] World Gold Council How Gold is Mined
[19] Knight Piesold Consulting Renewable Power for Mines

energy demands at DoD installations were met by a mix of energy sources including electricity (53%), natural gas (32%) and other fuel sources such as fuel oil and coal (15%).[20]

Micro-reactors are capable of supplying energy to a wide range of DoD installations, and are particularly well suited to power and heat remote domestic military bases that are a critical part of the national security infrastructure. Remote domestic military bases typically have significant energy needs, high electricity costs and significant carbon emissions.

Ninety percent of military installations have an average annual energy use that can be met by an installed capacity of nuclear power of 40 MWe or less.[21] It is anticipated that most DoD installations will utilize one or more micro-reactors in the 2 MWe to 10 MWe range. DoD is likely to first use micro-reactors for remote installations with critical missions. Eielson Air Force Base near Fairbanks, Alaska is an example of a remote installation that was discussed in the 2018 NEI *Roadmap for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations*.

3.4 International

Micro-reactors are capable of serving remote areas around the world. Canada is pursuing the use of micro-reactors in remote arctic communities as well as for mining operations.[22] The market needs and conditions for remote areas in Canada are very similar to those in the Alaska.[23] A 2014 report estimated the Australian off-grid electricity market to be at least 200 MWe and potentially more than 1,000 MWe.[24] In less developed countries, many communities do not have access to reliable electricity. In these communities, micro-reactors offer the possibility to dramatically improve the quality of life, for example, by providing powering the energy intensive processes needed to produce clean drinking water. It is noted that greater U.S. government support for export of micro-reactors will be needed to assure U.S. companies are competitive in international markets.

[20] DoD Annual Energy Management and Resilience Report FY2016
[21] CNA Feasibility of Nuclear Power on U.S. Military Installations, 2011
[22] A Call to Action: A Canadian Roadmap for Small Modular Reactors
[23] Gwich'in Council International Diverging from Diesel
[24] AECOM Australia's Off-Grid Clean Energy Market

4 MICRO-REACTOR COSTS

A reference two-unit 5 MWe micro-reactor plant, for a total capacity of 10 MWe, is used for cost estimates based upon input from several micro-reactor developers. NEI developed a proprietary economics model to calculate the Levelized Cost of Electricity (LCOE) to estimate the cost of generating electricity from a micro-reactor. Appendix A describes the reference micro-reactor and cost inputs, and Appendix B describes many of the micro-reactors technologies.

The costs are based upon NRC licensing and regulation oversight of the construction, operation and decommissioning of the micro-reactors. The NRC licensing process is mature, well understood and transparent; however, the NRC licensing process and regulations were not designed for micro-reactors. The NRC is pursuing a more efficient licensing process, including streamlined environmental reviews, which is needed to better suit the small size and risk of micro-reactors.

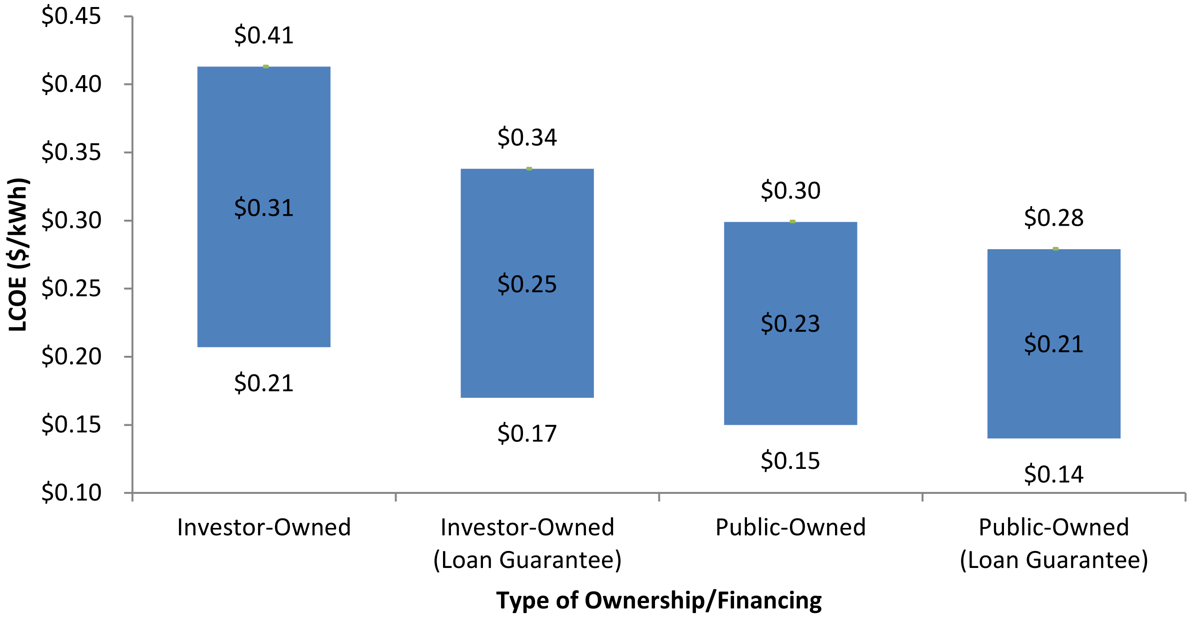
4.1 Costs for the First Micro-Reactor

Costs for the first micro-reactor are based upon 40 years of operation with refueling or reactor core replacement every 10 years. Early micro-reactors are likely to be co-located with existing generation sources to power large loads, such that the micro-reactor would be able to maintain a capacity factor of 95%. The site engineering and licensing costs are included in the capital costs for the micro-reactor. The first-of-a-kind design and licensing of the reactor itself are assumed to be amortized over the production of a large number of micro-reactors. The cost inputs for the first micro-reactor expressed as a nominal value with a lower and upper range are described in Appendix A.

There are a number of factors related to deployment conditions that can significantly impact the costs, including the transport accessibility, weather and climate, and labor conditions. Similarly, there are a number of factors related to the micro-reactor, such as the technology and balance of plant design that can significantly impact the costs. Financing of capital costs are also significant and are dependent upon the type of organization that owns the micro-reactor and the availability of loan guarantees. The need for additional transmission or distribution infrastructure is not included as it is assumed this would be needed regardless of whether a micro-reactor or another generation technology is used.

Given this variability, the LCOE of the first micro-reactor is estimated to be between $0.14/kWh and $0.41/kWh. Figure 1 shows the range of estimated LCOE for investor-owned utilities (IOUs), and public-owned utilities (e.g., municipals), with and without the use of loan guarantees. Differences in costs based on ownership type are mostly associated with financing. Therefore, costs for a private owner would be similar to those for an investor-owned utility.

Figure 1: Estimated Levelized Cost of Electricity Generation for the First Micro-Reactor



Production Tax Credits (PTCs) have been effective in promoting the deployment of renewable technologies for the past several decades. PTCs are also available for up to 6,000 MWe of nuclear capacity at a value of $0.018/kWh from the Energy Policy Act of 2005 and the subsequent extension in 2018.[25] We expect that the first micro-reactors will be deployed in the mid-2020s and would qualify for PTCs. The value of a PTC was not included in the cost estimates, but if it is included it would further reduce the LCOE by $0.008/kWh. If a PTC is modeled as an energy credit of $24 per MWh for 10 years escalated for inflation, similar to what is available for renewable sources, the reduction in LCOE would be $0.0135/kWh. Thus, PTCs are not expected to meaningfully promote the development of micro-reactors as they provide relatively little reduction in the price of electricity.

Most micro-reactors plan to utilize high-assay low-enriched uranium (HALEU) fuel that is enriched up to 20% of U-235. There is no current supply of HALEU, and commercial supply is not likely to materialize until a market is formed.[26] Therefore, DOE will need to provide HALEU for early micro-reactors. Demonstration of micro-reactors could also bring more certainty on micro-reactor costs, as well as identify opportunities to reduce those costs. HALEU and demonstration reactors are addressed in the Nuclear Energy Leadership Act that was introduced by Senator Murkowski and others in March of 2019.

4.2 Cost Sensitivities

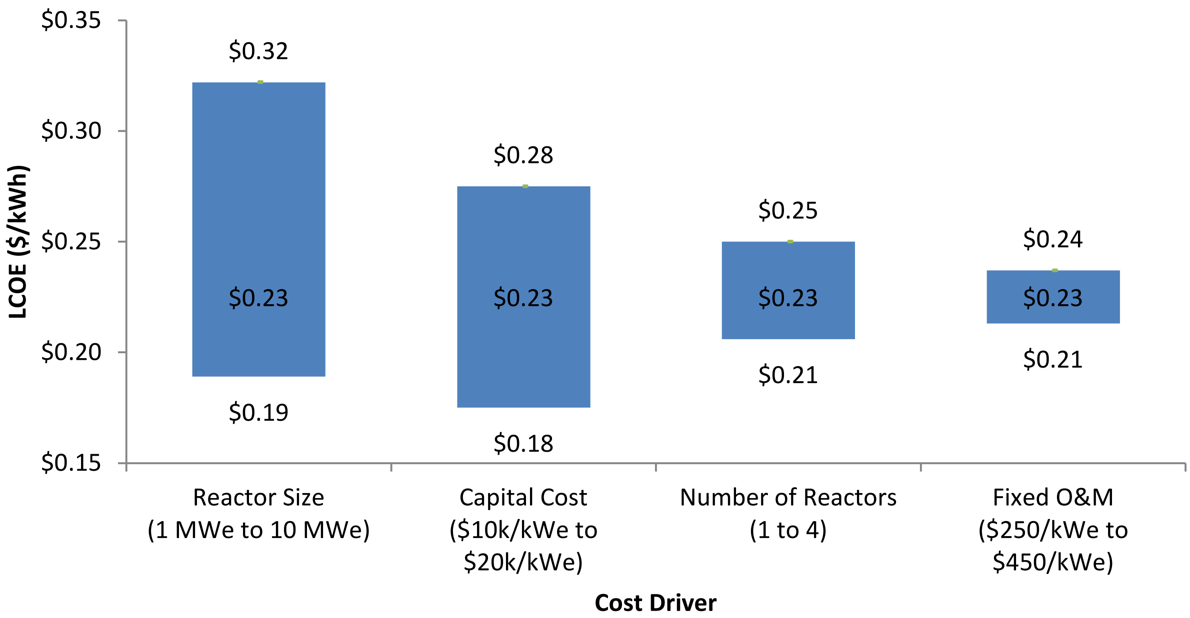
Given the range of LCOE for the first micro-reactor, it is important to understand the relative impact of key cost inputs. In Figure 2, the cost sensitivities are estimated based upon the range of costs described

[25] Vogtle 3&4 are expected to begin operations in 2021 and 2022 respectively and will use approximately 2,200 MWe of the 6,000 MWe available for the PTC. A PTC is also assumed to be transferable from public entities to non-public project participants.
[26] NEI Addressing the Challenges with Establishing the Infrastructure for the Front-End of the Fuel Cycle for Advanced Reactors

in Appendix A, and are calculated for a public-owned utility without loan guarantees, which would be similar for an investor-owned utility with loan guarantees. When assessing the sensitivity of a cost input, the other costs are held constant at the nominal inputs.

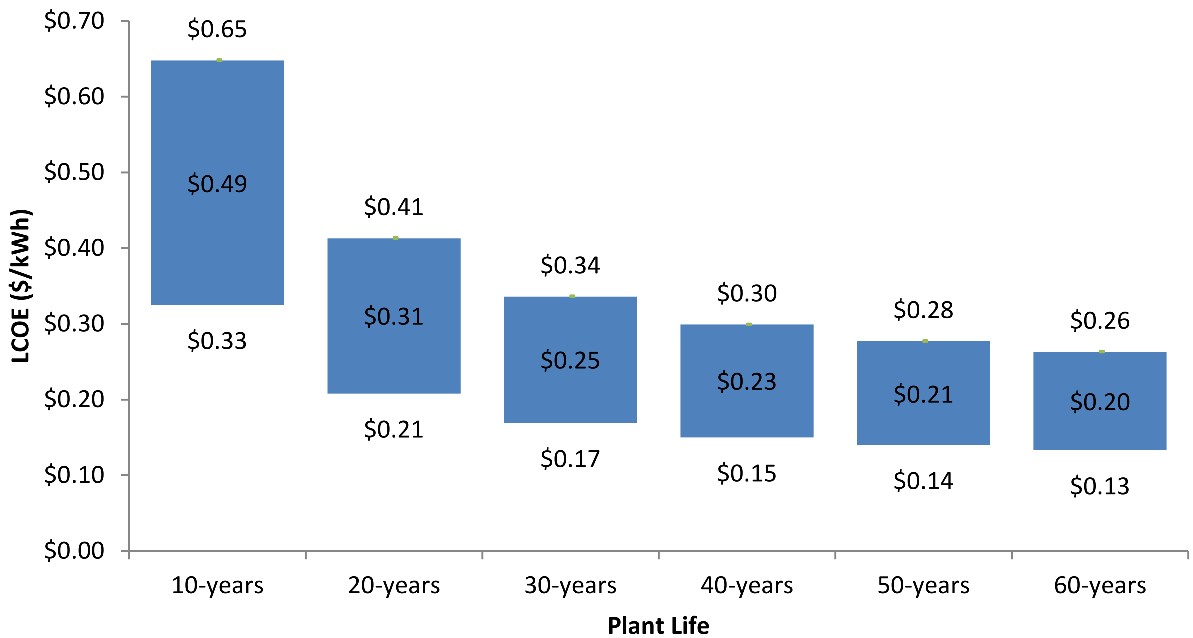
As expected, the reactor size and capital cost are the largest drivers of costs for a micro-reactor, with the number of reactors at the plant site and fixed O&M also having a significant effect on the LCOE. Although not shown, the core life, fuel costs and decommissioning costs all have relatively little impact, less than 5% each, on the LCOE.

Figure 2: Sensitivity of the Estimated LCOE to Cost-Drivers for the First Micro-Reactor



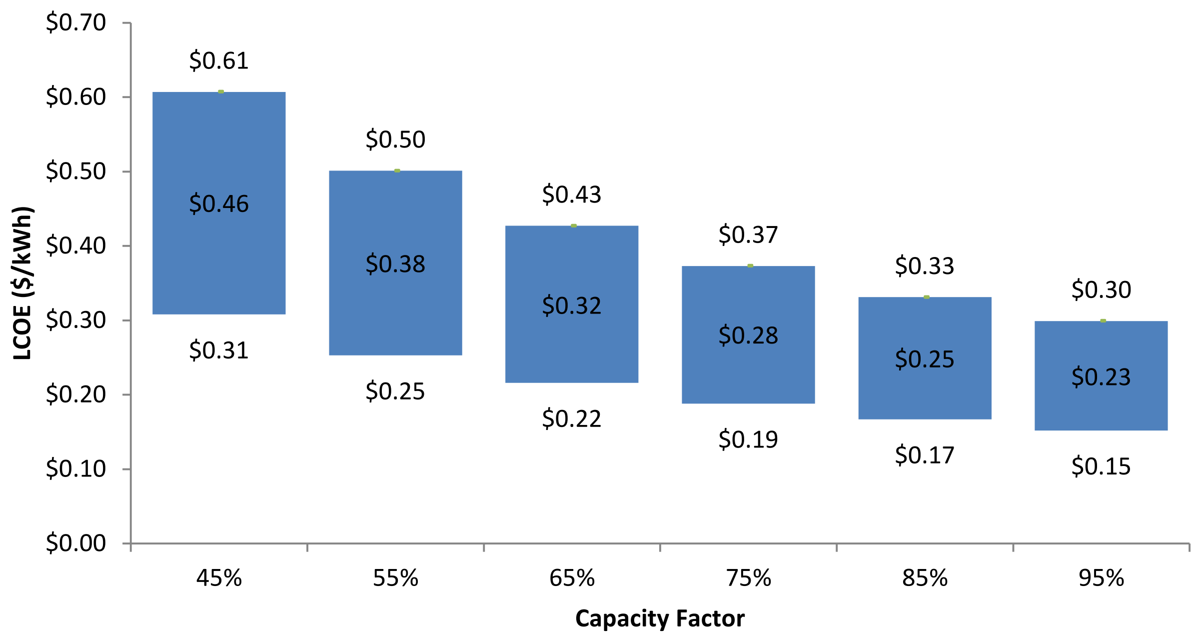
The cost estimate for the first micro-reactor assumes an operating life of 40 years with a 10 year refueling interval. However, existing nuclear power plants are capable of operating up to 60 or even 80 years, while some purchasers of micro-reactors may not need power from a micro-reactor for the full 40 years. Thus, it is important to understand the impact of the plant life on the LCOE of a micro-reactor. Figure 3 presents the estimated costs for the first micro-reactor with a plant life varying from 10 years to 60 years. The costs are calculated for a public-owned utility without loan guarantees, which would be similar for an investor-owned utility with loan guarantees.

Figure 3: Estimated LCOE of the First Micro-Reactors Based on Plant Life



In some cases, the micro-reactor(s) may not constantly operate at maximum output and therefore would not achieve the assumed maximum capacity factor of 95%. A sensitivity of the LCOE based on a range of capacity factors is provided in Figure 4. The results show that the LCOE of the micro-reactor roughly doubles at half the output. This is typical for a generation source that has a very low variable operating cost relative to the fixed costs. Micro-reactors with flexible operations could alternate between the generation of electricity and heat, or utilize battery storage to optimize the capacity factor and economics.

Figure 4: Sensitivity of Micro-Reactor LCOE on Capacity Factor



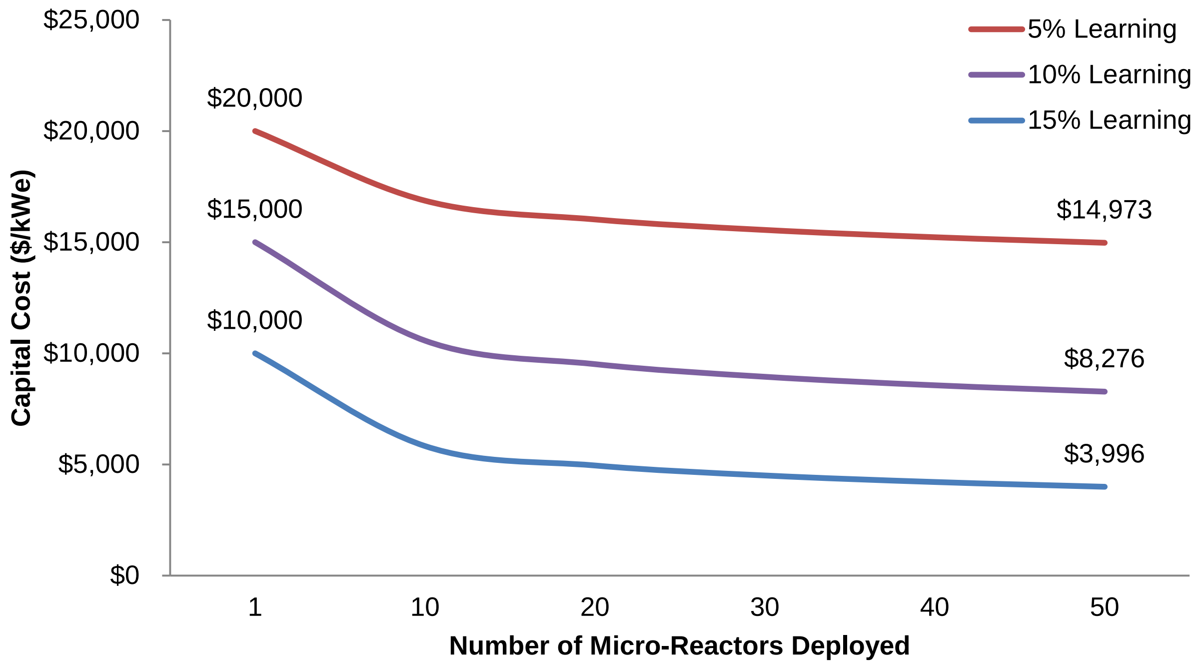
4.3 Costs of Future Micro-Reactor

Deployment of the first-of-a-kind of any technology is always more expensive than the next deployment. The cost reductions are mainly attributable to the incorporation of lessons learned from previous deployments. It is well established for nuclear power plants as well as for other industries that the cost reductions from lessons learned follow a pattern of a given percentage reduction, typically between 10% to 20%, for every doubling of units deployed. Korea Hydro and Nuclear Power and the U.S. Navy have experienced learning rates of a 15% cost reduction per doubling of units.[27,28]

[27] General Dynamics Affordable Small Modular Reactors - Effective Integration of Modular Design, Manufacturing and Construction Techniques
[28] EPRI The Role of Nuclear Power

Figure 5 estimates overnight capital costs for future micro-reactors based upon the range of initial overnight capital costs, and a range of learning rates, as described in Appendix A. The cost reductions are estimated based on continuous learning through the first 50 units.[29] The exact learning rate and number of units at which costs will stabilize (also called the Nth-of-a-kind costs) is design specific. Designs that are completely produced in a factory are expected to experience higher learning rates for more units as compared to designs with relatively more on-site construction. The size and complexity of the design is also expected to influence the learning rate and point at which costs stabilize. Producing micro-reactors in dedicated factories are expected to result in higher learning rates than fabrication in factories with mixed products.

Figure 5: Micro-Reactor Learning Curve Capital Cost Reduction



Other cost reductions for future micro-reactors are expected as well. Fuel costs could be reduced as more units are produced since many of the designs will use novel fuel that is not produced in bulk today. Operation and maintenance costs are also expected to be reduced from learning through operating experience. While these cost reductions are expected, they are not included in this analysis.

[29] The Harris School Energy Policy Institute at Chicago, Small Modular Reactors - Key to Future Nuclear Power Generation in the U.S.

5 MICRO-REACTOR COMPETITIVENESS

The existing energy sources in remote areas, in most cases, are diesel generators that rely on an off-site supply and on-site storage of large amounts of fuel. Diesel generators are not only expensive to operate, they also emit carbon dioxide and other air pollutants and can be unreliable.

Although the market price of electricity is readily known, it is difficult to find data on the generation costs, which are more appropriate to compare against the estimated LCOE for generation from micro-reactors. Thus, generation costs are calculated for various types of markets based on estimates of costs for conventional sources of electricity in remote areas. The cost of generating electricity from diesel engines in remote arctic communities is estimated to be $0.30/kWh to $0.60/kWh as discussed in Appendix C.[30,31] Island communities and remote mining have similar electricity prices that are lower than Arctic communities due primarily to reduced fuel transportation costs. Based upon comparisons of the diesel fuel costs in Arctic communities, the cost of generation for island communities and remote mining is assumed to be $0.15/kWh to $0.35/kWh.

Remote defense installations are likely to have generation costs that are similar to the costs for nearby communities and mining operations, whether they are in arctic or island communities. Micro-reactors are clearly competitive for defense installations with current costs above $0.40/kWh. For defense installations with electricity generation costs below $0.25/kWh, the economic competitiveness of the first micro-reactors are less certain if the benefits of highly resilient, reliable and clean power are not valued. Thus, a current generation cost of $0.23/kWh to $0.25/kWh at a remote defense installation is used to assess whether micro-reactors could be competitive in markets that may be willing to pay more for highly resilient energy.

While the DoD has required energy resilience for its installations, the agency has not quantified the value of assured access to electricity for critical operations performing national security missions.[32] Hence, this report proposes a conservative premium of $0.05/kWh to $0.07/kWh based upon discussions with national security experts. Thus, we use a range of $0.28/kWh to $0.32/kWh to assess the cost competitiveness of micro-reactors for remote defense installations needing highly resilient electricity generation sources. Enhancements to Federal Power Purchase Agreement authorities, like those proposed in the Nuclear Energy Leadership Act introduced by Senator Murkowski and others, would help reduce the costs of micro-reactors used at defense installations.

The generation costs for larger grids are included as a reference to compare against future micro-reactors with lower costs. The Alaska Railbelt is the area from Fairbanks to Anchorage that is home to most of the state's population and uses 78% of the electricity in the state.[33] The cost of electricity generation in the Alaskan Railbelt is estimated at $0.06/kWh to $0.15/kWh, based on electricity prices that range from $0.14/kWh to $0.23/kWh, which implies that other costs, including electricity delivery, are $0.08/kWh. Electricity generation costs in the continental U.S. are estimated to be $0.03/kWh to

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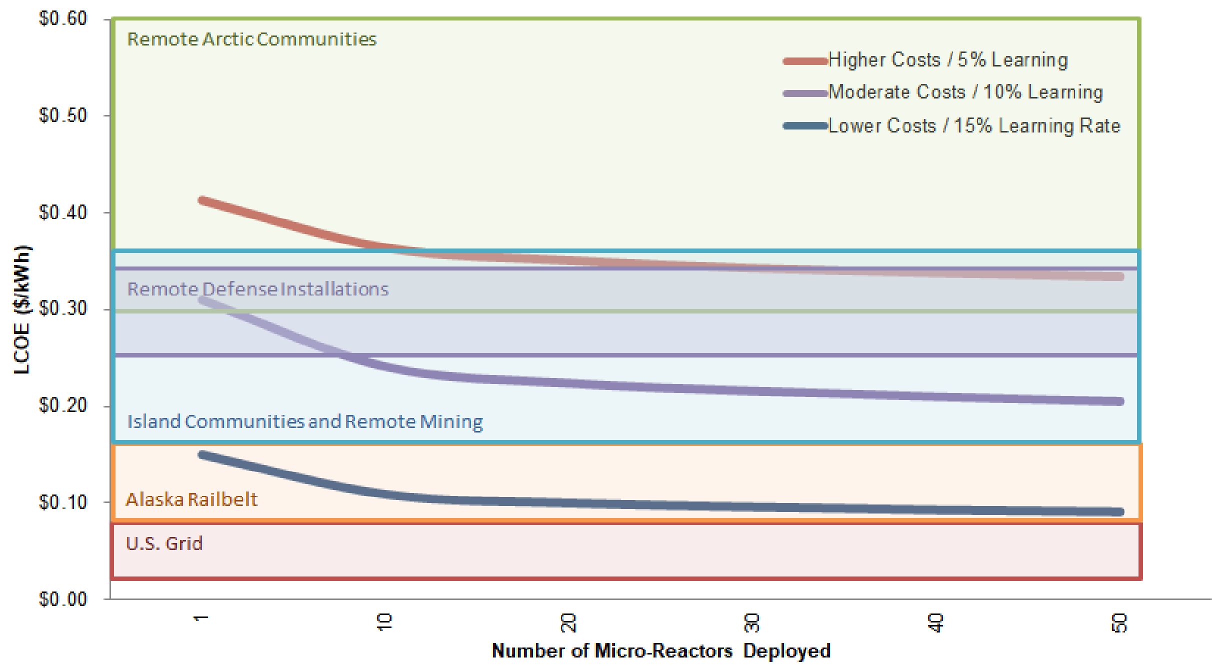
[30] Journal of Renewable and Sustainable Energy An Alaska Case Study: Diesel Generator Technologies
[31] Alaska Energy Data Gateway Community Data Summaries
[32] DoD Instruction 4170.11, Installation Energy Management
[33] Alaska Energy Statistics 1960-2011, Prepared December 2013

$0.08/kWh based on electricity prices that range from $0.05/kWh to $0.17/kWh, and electricity delivery costs around $0.03/kWh.[34]

In Figure 6, the expected costs of the first and future micro-reactors are compared against the current LCOE in the various target markets. These future costs reflect the estimated cost reductions from lessons learned as discussed in Appendix C. The high and moderate LCOE cost projections are based upon the nominal and upper range of costs in Appendix A for an investor-owned utility to approximate a more conservative estimate of future costs. The low LCOE cost projection is based upon the lower range of costs in Appendix A for a public-owned utility to provide a more optimistic estimation of future micro-reactor costs.

Figure 6: Micro-Reactor Cost Competitiveness



The analysis shows that micro-reactors can be cost competitive for arctic communities, islands, mines and defense installations. Deployment of micro-reactors could significantly reduce the costs of electricity and state subsidies for Alaskan PCE communities. There are also scenarios where micro-reactors can be competitive in the Alaska Railbelt, and for secure micro-grids that have requirements for highly resilient power. Micro-reactors provide a combination of benefits not provided by other available energy sources—namely they are a highly resilient, carbon-free, flexible, and can produce electricity on-demand. Micro-reactors are expected to be available for deployment in the mid-2020s. The small size and potential to produce a large number of micro-reactors are expected to help rapidly reduce costs and accelerate deployment of future micro-reactors.

[34] Energy Information Administration. Note that while generation costs in some parts of the U.S. could reach $0.14/kWh, this report assumes that new generation on the continental U.S. grid will need to be below $0.08/kWh.

APPENDIX A: INPUTS AND ASSUMPTIONS

The cost analysis is performed on the following reference micro-reactor, which is established based upon input from several micro-reactor developers. The nominal micro-reactor is used to perform sensitivity analyses.

	Nominal	Range
Reactor Size (MWe)	5	1 to 10
Number of Co-Located Reactors	2	1 to 4
Plant Life (Years)	40	10 to 60
Core Life (Years)	10	5 to 20
Capacity Factor	95%	45% to 95%

The estimated LCOE for the first micro-reactor is based on the following generic cost inputs, which are established based upon input from several micro-reactor developers. These are expected to envelope the range of potential conditions, including transport accessibility, weather and climate, labor conditions, reactor technology and balance of plant design.

	Nominal	Range
Overnight Capital Cost ($/kWe)	$15,000	$10,000 to $20,000
Fixed Operations and Maintenance Cost ($/kWe)	$350	$250 to $450
Fuel Cost ($/MWh) (including used fuel management)	$10	$6 to $14
Decommissioning Cost ($/MWh)	$5	$3 to $7
Cost per Refueling (transport and installation, excluding Fuel, which is captured above)	$20 million	$13 million to $27 million

The following financial inputs were assumed for the analysis in order to bind the potential ownership and financing conditions for micro-reactor projects.

	Investor-Owned Utility	Investor-Owned Utility with Loan Guarantee	Public-Owned Utilities	Public-Owned Utilities with Loan Guarantee
Cost of Debt	5.5%	4.3%	4.5%	3.9%
Cost of Equity	15%	15%	N/A	N/A
Debt to Equity Ratio	55%	80%	N/A	N/A
Tax Rate	21%	21%	N/A	N/A
Inflation Rate	2.0%			
Debt Term	15 years			
Depreciation	10 year, straight-line			

While one study found learning rates for conventional nuclear power plants around 1,000 MWe in size have been negative to 6%, other generation sources have had learning rates up to 45%. More recently KHNP has experienced learning rates around 15% for the APR-1400. Micro-reactors are expected to more closely follow the learning rates for manufactured products due to their small size and focus on factory fabrication, for which industries like aerospace, shipbuilding and automotive have seen learning rates of 15% to 20% .[35,36,37] It is expected that the learning rate for micro-reactors will be between 5% and 15%. The learning curve is only applied to the overnight capital cost for simplicity and because this is the main driver of costs for micro-reactors. Fuel costs could be reduced as more units are produced since many of the designs will use novel fuel that is not produced in bulk today. Reductions in O&M that come with learnings and larger fleets of micro-reactors could also reduce the generation costs of future micro-reactors a few cents per kWh. To cover the largest range of possible future costs, the potential cost reduction through learning is applied with a lower learning rate for the higher initial cost estimate and a higher learning rate for the lower initial cost estimate, as follows:

	Initial Overnight Capital Cost ($/kWe)	Cost Reduction Per Doubling of Units	50th Reactor Capital Cost ($/kWe)
Low Rate of Learning	$20,000	5%	$14,973
Average Rate of Learning	$15,000	10%	$8,276
High Rate of Learning	$10,000	15%	$3,996

[35] U.S. EPA Cost Reduction through Learning in Manufacturing Industries and in the Manufacture of Mobile Sources
[36] Energy Policy A Review of Learning Rates for Electricity Supply Technologies
[37] Strategos Learning & Experience Curves in Manufacturing

APPENDIX B: MICRO-REACTOR TECHNOLOGIES

A number of companies are developing micro-reactors. The following descriptions of these designs are for information only and were not used to perform the cost estimates for the reference micro-reactor.

B.1. Elysium

Elysium is developing a Molten Chloride Salt Fast Reactor at low pressure in the range of 4-100MWe, but the reactor can be operated as rapid load following, or as low as 10% power. The NSSS is road shippable and does not change size strongly for various power levels, and the power conversion system and control shipped on a separate vehicle. For micro-reactors, the fuel lifetime is indefinite. The system is an Open Air Gas Turbine, with no water cooling required for operation or decay heat cooling. Process heat up to 650C is available for sulfur-iodine synthetic fuel production locally for vehicles or backup power, or many other process heat uses, like heat based Combined Cooling Heating Power (CCHP, district heating and cooling, desalination, etc.

B.2. Flibe Energy

Flibe Energy is developing a family of micro-reactor designs in the 20-50 MWe performance range. These would be responsive electrical sources for a class of distributed electrical loads that have a high degree of variability and autonomy. Supercritical carbon dioxide power conversion systems would be coupled with a low-pressure, high-temperature liquid-fluoride nuclear reactor to generate electrical power at 40-45% thermal efficiency. Subsystems for fully independent restart capability will be included in the design. This technology combination is anticipated to result in a compact form factor amenable to transport.

B.3. General Atomics

General Atomics (GA) is developing a mobile nuclear power supply that fits within a standard CONEX container and is capable of autonomous generation of 4-10 MWe with a refueling period greater than 10 years. The compact power supply builds on GA’s development of high temperature materials and fuels which enable high performance, a high degree of safety and protection against potential threats. It is also able to rapidly respond to large fluctuations in small military base loads. Its autonomous features derive from GA’s integrated defense systems (e.g., unmanned aircraft interdiction and reconnaissance missions) and supply of military hardware for power production, communications and mission control. The design also builds on GA’s experience in supplying dozens of research reactors under 10 MWt and GA’s work on an advanced commercial reactor.

B.4. HolosGen

Holos is a mobile modular nuclear power generator ready to operate immediately upon deployment, with enhanced safety features optimized to produce affordable pollutant-free electricity and process-heat. Holos power conversion system are integrated and sealed altogether with subcritical reinforced fuel cartridges. Each generator can operate as a stand-alone electric island at sites with no, or weak, power grid infrastructure and offers scalable power rating, to meet local electric demands with autonomous high-resolution load-following capabilities. Specialized Holos configurations can be timely deployed to supply emergency electricity and process-heat to disaster areas and to remote locations.

Holos core is formed by coupling multiple fuel cartridges housed within independent and sealed subcritical power modules representing an operational generator fully comprised within International Standards Organization (ISO) transport containers. Cooling of Holos subcritical fuel cartridges solely relies on environmental air with passive decay heat removal. At the end of the fuel cycle, the fuel cartridges fit within licensed transport canisters for long-term fuel storage with reduced thermal loading and decommissioning cost. Holos eliminates the balance of plant and its components size enables true economies of scale production with safety performance validation and factory certification with substantially reduced costs and licensing time. Holos innovative architecture provides a distributable power source satisfying various applications' requirements, highly competitive in today's market and synergetic with technologies sourced on renewable energy.

B.5. Hydromine

Hydromine's LFR-AS-200 / LFR-TL are innovative Gen IV lead-cooled fast reactor ("LFR") design concepts that aim to achieve increased efficiency, lower cost, smaller size, and improved safety through natural mechanisms and simplified systems. The LFR-AS-200 is designed for small reactor application with a 200MWe capacity while the LFR-TL is a micro reactor concept for 5-20 MWe. While LFRs already achieve ~50% enhanced efficiency over conventional light-water reactors, Hydromine's design concepts can further improve efficiency by eliminating large/expensive installations, the significant cooling water requirements, large fuel consumption, and large production of waste materials. Hydromine's design concepts increase safety and efficiency by eliminating components, decreasing size and complexity, and eliminating volatile elements that react violently to both air and water.

B.6. NuGen

The NuGen Engine™ being developed by NuGen is a robust single-module, direct-cycle gas-cooled microreactor. Within the single module, its patented innovative fuel core is fully integrated with the reactor's other components and systems. The NuGen Engine™ is a safe and simple microreactor that offers reliability, manufacturability, scalability, adaptability and versatility. Its output is scalable between 1-50 MWe and it offers process heat for cogeneration and direct mechanical energy for propulsion (watercraft and underwater drones). NuGen's current design efforts are focused on an autonomous transportable ultra-compact engine for use at military bases, other national security locations and remote locations. This design is adaptable for other off-grid uses and lunar applications.

B.7. NuScale

NuScale is exploring additional next generation reactor designs beyond its flagship 60 MWe NuScale Power Module (NPM). NuScale envisions offering two next-generation reactor types: A 10-50 MWe next generation NPM and a 1-10 MWe heat pipe reactor. Design concepts under evaluation can accommodate fuel enriched to less than 5.0% U-235 or HALEU fuel which allows for extending core life to 10 or more years. The 10-50 MWe Next Generation NPM builds on NuScale's existing SMR technology and licensing expertise (see NRC Docket No. 52-048), the concept for a next generation NPM is intended for smaller power plant applications. NuScale is also evaluating the 1-10 MWe heat pipe reactor, simple and inherently safe compact heat pipe cooled reactor concepts that require little site infrastructure, can be rapidly deployed, and are fully automated during power operation. All heat pipe reactor concepts under evaluation are non-light water reactors.

B.8. Oklo

Oklo is developing a compact 2 MWe fast spectrum reactor. It is designed to serve remote, rural and native communities as well as industrial and military sites. The reactor operates purely on natural physical forces, with very few moving parts. The reactor is designed to operate for up to 20 years before refueling, and uses HALEU fuel.

B.9. StarCore Nuclear

StarCore Nuclear is developing a modular High Temperature Gas-cooled Reactor, designed specifically to support remote locations. The inherently safe design makes use of HALEU TRISO fuel in a prismatic block core, to provide heat for an externally-fired, air-breathing gas turbine. The advanced control system supports fully automated operation, although the initial plants will include plant operators. The power output can range from 10-120 MWe depending on the number of modules constructed. The plant is highly flexible and configurable to provide load-following electricity, heat, water purification, hot water/steam or hydrogen as needed to support local communities and industry.

B.10. TerraPower

TerraPower is developing the Molten Chloride Fast Reactor (MCFR) to serve grid-scale electricity production. As part of the MCFR product portfolio, TerraPower is evaluating a MCFR micro-reactor concept in the 1-10 MWe reactor size range. The MCFR micro-reactor is built upon TerraPower’s molten salt reactor design and testing expertise. An initial reactor is planned to serve as a physics demonstration unit that will leverage existing technologies. A commercial MCFR micro-reactor is being considered to operate with high availability for >10 years without refueling utilizing HALEU fuel at temperatures exceeding 700°C.

B.11. U-Battery

U-Battery is developing a micro modular reactor designed primarily for energy intensive industry and remote locations. It generates 10 MWt which can be delivered in a CoGen configuration with up to 4 MWe electricity and 750°C process heat. It is gas cooled - helium in primary circuit, nitrogen in secondary circuit – and is powered by high integrity TRISO fuel, providing inherent safety. U-Battery can be deployed locally to demand, eliminating grid and infrastructure costs. Its modularity permits quality assurance and testing during the manufacturing stage, while minimizing civil construction times, reducing construction risk and financing costs, and easing transportation to customers globally. The expected lifespan of a U-Battery unit is 60 years with a five year refueling cycle. Other potential applications of U-Battery include: back-up power to large nuclear reactors; solutions for water scarce areas through desalination; and generation of hydrogen for hydrogen-powered vehicles.

B.12. Westinghouse

The Westinghouse eVinci micro-reactor is a semi-autonomous, transportable, and scalable energy generator ranging from 200 KWe to 15 MWe. The eVinci, which is an evolution of the Los Alamos National Lab’s *Megapower* concept and advanced heat pipe technology, is designed to provide combined heat and power for military installations, remote communities and mining installations for high resiliency operation. The eVinci utilizes HALEU and has a solid state reactor with minimal moving parts and is being targeted to operate for at least 10 years without refueling, and maintenance.

B.13. X-energy

The X-energy X-battery is a road transportable high temperature, gas-cooled pebble bed reactor with a thermal rating of 10 MWt. It features HALEU graphite pebble fuel elements with UCO TRISO fuel particles. The reactor can be run autonomously, without any operators present on-site, or in first of a kind demonstration plants to require very few operators. The Xe-100 MICRO reactor is designed to be flexible in its application and can be configured to use a combination of power and heat, and to support the production of hydrogen. Various advanced fuel cycles have been tested in the past, such as the (Th,U)O2 can operate for around 10 years with a single core load.

B.14. Other Developers

Other companies that may also be developing micro-reactor designs include LeadCold Nuclear and Ultra Safe Nuclear Corporation. Descriptions of these other designs are not included in this report due to limited public information on these designs.

APPENDIX C: CURRENT COST OF ELECTRICITY GENERATION FROM DIESEL

Micro-reactors are particularly well-suited to markets that currently use diesel generators to produce electricity. There is no clear data on the costs of electricity generated by diesels in these markets, so a simplified model was created to estimate the current generation costs from diesels.

It was assumed that the cost of diesel fuel and the transportation of the fuel dominate the total generation cost for diesels. It is assumed that the diesel generators have been installed for over 10 years and thus the capital and financing costs are zero. For reference, the capital cost of a diesel generator was $1,672/kWe in 2016, and is typically 5% of the LCOE for a new diesel generator.[38] O&M costs are similarly dwarfed by the diesel fuel and fuel transportation, and were assumed to be relatively small since an estimate of O&M costs could not be found.

The average cost of diesel fuel in Alaska in FY18 was $2.86/gallon, and in 2014 ranged between $3.38/gallon and $4.89/gallon, when the average cost was $4.21/gallon.[39,40] In fact, the price of diesel fuel in 2017 and 2018 are considerably lower than the previous eight years. The efficiency of diesel generators appears to vary between 11 kWh/gallon to 14 kWh/gallon.[41, 42,43] This results in a calculated cost of electricity generation between $0.20/kWh and $0.44/kWh.

This appears very conservative in some areas given the price of electricity to consumers in Alaska's PCE communities in 2014 ranged from $0.41/kWh to $1.02/kWh, and implies that other costs related to electricity delivery, indirect expenses, taxes, etc. would range from $0.20/kWh to $0.58/kWh or more. These estimates are also much lower than other cost estimates for new diesel generation of $0.40/kWh to $0.80/kWh at $3/gallon diesel fuel. [44,45]

Based upon this data, this report assumes that micro-reactors would compete against diesel generation costs of $0.30/kWh and $0.60/kWh in Alaska's PCE communities. This implies that other costs, including electricity delivery, range from $0.11/kWh to $0.42/kWh.

Island communities and remote mining have similar electricity prices ranging from roughly $0.20/kWh to $0.40/kWh, which are lower than arctic communities primarily due to reduced fuel transportation costs. In these more accessible of the remote locations, the cost of generation is assumed to be $0.15/kWh to $0.35/kWh, which implies that other costs, including electricity delivery are $0.05/kWh, which is higher than the U.S. average of $0.02/kWh to $0.03/kWh.[46]

[38] U.S. Energy Information Administration Construction Cost Data for Electric Generators Installed in 2016
[39] Alaska Energy Authority Power Cost Equalization Program
[40] Alaska Energy Data Gateway Community Data Summaries
[41] Diesel Service and Supply Approximate Diesel Fuel Consumption Chart
[42] Breyer, et. al. Electrifying the Poor: Highly Economic Off-Grid PV Systems in Ethiopia - A Basis for Sustainable Rural Development
[43] University of Ontario The Ring of Fire Priority Setting for Nuclear Power in the North
[44] Institute of Social and Economic Research - University of Alaska Anchorage Electricity in Alaska: A Growing and Changing Picture
[45] U.S. Energy Information Administration
[46] EIA Today in Energy