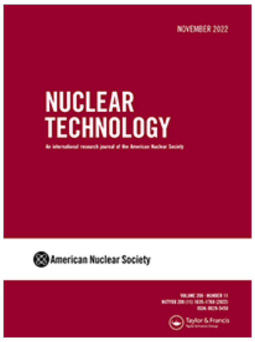

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Critical Review

Prospects for Nuclear Microreactors: A Review of the Technology, Economics, and Regulatory Considerations

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Abstract — *The nuclear energy sector is actively developing a new class of very small advanced reactors, called microreactors. This technology has disruptive potential as an alternative to carbon-intensive energy technologies based on its mobility and transportability, resilience, and independence from the grid, as well as its capacity for long refueling intervals and low-carbon emissions. Microreactors may extend nuclear energy to a new set of international customers, many of which are located where energy is at a price premium and/or limited to fossil sources. Developers are creating designs geared toward factory production where quality and costs may be optimized. This paper reviews the existing literature on the technology, potential markets, economic viability, and regulatory and institutional challenges of nuclear microreactors. The technological characteristics are reviewed to describe the wide range of microreactor designs and to distinguish them from large nuclear power plants and small modular reactor (SMR) designs.*

The expanding literature on the cost competitiveness of SMRs relative to other nuclear and nonnuclear technologies is also reviewed, with an emphasis on understanding the challenges of making microreactors economically viable. A major part of this study focuses on the deployment potential of microreactors across global markets. Previous work on SMR market assessment is reviewed, and the adaptation of these studies to the deployment of microreactors is more fully examined. Characteristics that differentiate microreactors from SMRs and other energy technologies may make microreactors suitable for unique and localized applications if they can be economically competitive with other energy technologies, as well as meet regulatory and other societal requirements. Recent research on global markets for microreactors is evaluated and extended in this paper to a previously unevaluated use case in which microreactors can play a role in grid resiliency and integration with renewables. Further challenges associated with the commercialization of microreactors, in addition to cost competitiveness, are explored by examining the regulatory and safety challenges of microreactor deployment.

Keywords — *Microreactor technology, nuclear economics, nuclear markets, nuclear regulation and safety, deployment indicators.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

As detailed in reporting by the Intergovernmental Panel on Climate Change,[1] considerable increases are needed in the share of low-carbon energy within our global energy mix in order to achieve climate change

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mitigation goals globally. Along with further development of renewable energy production, low-carbon baseload energy sources as well as technologies capable of load-following can support the attainment of net-zero carbon emissions in global energy generation. Nuclear energy's share of nearly 20% of total electricity production in the United States and 10% worldwide[2] represents an area where new nuclear technologies can play an important role in low-carbon energy development. The potential increases if one considers the extent to which microreactors are able to enter new markets where large-scale energy technologies are not suitable.

Microreactors are among the emerging nuclear energy technologies with the potential to provide low-carbon energy. These are very small reactors utilizing advanced light water reactor (LWR) and non-LWR designs with power levels anticipated generally ranging from less than 1 MW(electric) to 20 MW(electric), with a maximum of 50 MW(electric). The reactors can generate energy for electricity, process heat for direct use, or both.[3] In heat operations, microreactor capacity is often described in terms of megawatt thermal [MW(thermal)], which varies based on the thermal efficiency (e.g., 33%) of the reactor. If hurdles can be overcome regarding the cost of manufacturing and operations, as well as the regulatory and institutional challenges, microreactors have the potential to fill unmet needs in energy portfolios where fossil fuel limitations are evident (e.g., diesel costs and transport). Microreactors may also become competitive where large electricity grids are not in place, where fuel delivery is cumbersome or expensive, where economies of scale are absent, or where renewables may not be an option due to space limitations or specific weather conditions.

The ongoing technology evolution of microreactor designs provides both opportunities and challenges for the commercial implementation of microreactors in energy portfolios. Advances with microreactors may support national low-carbon policies as well as resilience aims, where extreme weather events and other unplanned interruptions create conditions that undermine the security, safety, and/or economic stability of regions.[4–6] The U.S. Department of Energy (DOE) estimates, for instance, that power outages alone cost American businesses $150 billion per year, with approximately 80% of the outages caused by severe weather.[7] The COVID-19 pandemic and related increases in telework activity also highlight the importance of uninterrupted power and energy security, which microreactors may support. Such utilization for resiliency objectives could advance readiness for and recovery from disruptions, while ensuring continuity of operations in critical uses, such as power for key government functions, energy-intensive industries, emergency hospitals, and high-speed networks for home workers.

While economic challenges remain for the cost competitiveness of microreactors relative to other low-carbon sources of energy, some cost projections for microreactors indicate that they may well compete in markets unsuitable for larger nuclear technologies. For example, microreactor designs enable entirely different operating concepts, including use with mobile generation, such as in recovery efforts, or potential semi-remote operation. Specific to low-carbon energy production, large nuclear plants are not suited for smaller applications, use with microgrids, or use for small cogeneration applications, and they require large emergency planning zones.[8–10]

To review the status of microreactors and how to consider their adoption potential, we first discuss the profile of the microreactor technology, drawing distinctions with large nuclear power plants (NPPs) and small modular reactors (SMRs), and reviewing aspects of microreactor technology developments and commercialization. Key research on the costs and economic viability of microreactors is discussed in more depth to highlight the challenges for commercialization. Next, prospective markets are examined in relation to the unique features of microreactors and complementary implementation technologies to identify niche markets, termed profile markets, that are amenable to microreactor deployment. This paper summarizes recent research on the methods for analyzing global market potential for smaller nuclear technologies and the adaptation of these approaches to microreactors. This paper builds on a 2021 study, "Global Market Analysis of Microreactors," conducted under the DOE Microreactor Program.[3] It includes updated information on microreactor technology and small reactor economics and markets. Deployment potential is balanced by a discussion of regulatory challenges and institutional needs. Finally, we close with a review of key discussion points and concluding thoughts.

II. REVIEW OF TECHNOLOGY DESIGNS AND COMMERCIALIZATION DEVELOPMENTS

Microreactors (including a special class of reactors called nuclear batteries[11]) are a subset of SMRs, a category of nuclear reactors designed with smaller capacities required for portability. They generally range from less than 1 MW(electric) to 20 MW(electric) [maximum of 50 MW(electric)] and may be deployed for isolated, distributed, and embedded energy applications. Specific to low-carbon energy production, microreactors are suited for smaller applications, connection with renewable sources through minigrids and microgrids, replacement of fossil fuel sources in cogeneration applications, and other applications.[3]

Small modular reactors generally extend beyond microreactor capacities, ranging from 50 up to 300 MW(electric) per reactor module,[12] with some multiunit SMRs achieving around 900 MW(electric) total capacity. In contrast to traditional, large-scale NPPs with single-unit capacities of 600 to 1750 MW(electric), microreactors and the broader class of SMRs represent technology change, featuring reactor modularity and factory construction, smaller facility footprints, prospective reduction in emergency planning zones,[9] and more efficient construction associated with standardization, component sizing, fabrication, advanced joining techniques, and supply chains. The compactness of microreactors allows the reactor and power conversion system to be transportable, with the potential for mobile operations.[4] Microreactors are further distinguished by design simplicity and the potential for semiautonomous or remote operation with reduced operating staffs (see Sec. VI for safety and regulatory implications). Reactor designs may also include features to address aspects of proliferation, such as using a solid reactor core to encapsulate the fuel.[13]

Microreactors and SMRs reflect a broad technology spectrum including LWRs, high-temperature gas reactors (HTGRs), and advanced reactor concepts [e.g., liquid-metal fast reactors (FRs), molten-salt reactors (MSRs) and heat pipe (HP) reactors]. Designs may vary significantly in terms of fuels, materials, coolant, reflectors, manufacturing techniques (e.g., additive manufacturing), and heat exchangers.[14]

First-mover SMRs will likely use low-enriched uranium (LEU) fuel[12] with typical enrichments of 3% to 5% ^{235}U. By contrast, microreactor designs are typically based on high-assay low-enriched uranium (HALEU) fuels with enrichments above 5%, but below 19.75% ^{235}U. This higher enrichment level improves reactor performance and extends refueling intervals from several years up to the life of the reactor.[4] Economic evaluations by the Massachusetts Institute of Technology[15] (MIT) suggest that microreactor fuel costs may be high. Given this, the benefits from more expensive fuels must be weighed against performance requirements and the current limitations in manufacturing these fuels.

The simplest microreactors have HP designs that optimize energy transfer, avoiding the need for pumps to circulate their coolant.[4] Microreactors based on HTGR technology use tristructural isotropic (TRISO) fuel, the same that is used by larger HTGR designs. When higher temperatures (700°C to 1000°C) are needed (e.g., for some industrial applications), HTGR technology is most suitable. For FR technology, featuring compactness and fuel efficiency, proven oxide fuel may be used or more experimental metallic or nitride fuel. The experimental fuels are envisioned to be more robust for microreactors, where the fuel remains in the reactor core for much longer periods than in traditional reactors, resulting in higher radiation exposures.

Multiple international microreactor design initiatives are underway for MSR, HTGR, SFR, and HP technologies, with a sample of U.S designs shown in Table I. These highlight the diversity of designs, with refueling ranging from 3+ to 20 years and graphite as a common moderator. Looking more broadly, microreactors are under development in Europe with U-Battery, for instance, by Urenco in the United Kingdom and SEALER by LeadCold in Sweden. Companies in Russia and Japan are also developing microreactors up to 30 MW(thermal) (Ref. 2).

Currently, American and Canadian national energy laboratories are conducting microreactor technology demonstrations leading to commercial and/or defense applications. The U.S. Department of Defense in March 2020 exercised contract options for two teams led by BWXT Advanced Technologies LLC, Lynchburg, Virginia, and X-energy, LLC, Greenbelt, Maryland, to begin design work on a mobile nuclear reactor prototype under a Strategic Capabilities Office initiative called Project Pele. Demonstration of the first microreactor in the United States is targeted for the mid-2020s and would likely be commercially owned and operated with U.S. Nuclear Regulatory Commission (NRC) licensing.[16] Announcements by the U.S. Air Force in October 2021 identified a site in Alaska for a microreactor pilot,[17] and Canada is studying microreactors as a “feasible alternative” to diesel generation at mines and in remote communities.[18]

When comparing traditional NPPs, SMRs, and microreactors, one should keep in mind that all three represent not a single reactor design, but a category of multiple designs. For the traditional, large-scale NPP, the LWR class has become the dominant design, whereas other technologies like high-temperature reactors and FRs have yet to be fully commercialized. By contrast, SMR designs reflect multiple technologies, including both LWR and non-LWR. LWR thermal reactor technology is used for very few microreactors, based on design

TABLE I

Summary of Current U.S. Microreactor Designs and Technical Specifications*

Developer	Name	Technology Type	Power Output [MW(electric)/ MW(thermal)]	Fuel	Coolant	Moderator	Refueling Interval
Alpha Tech Research Corp.	ARC Nuclear Generator	MSR	12 MW (electric)	LEU	Fluoride salt	—	—
BWXT	BANR	HTGR	17 MW(electric)/ 50 MW(thermal)	TRISO	Helium	Graphite	5 years
General Atomics	GA Micro	HTGR	1 to 10 MW(electric)	—	Gas	—	—
HolosGen	HolosQuad	HTGR	13 MW(electric)	TRISO	Helium/ CO_2	—	10 years
Micro Nuclear, LLC	Micro Scale Nuclear Battery	MSR/HP	10 MW(electric)	UF4	FLiBe	YH	10 years
NuGen, LLC	NuGen Engine	HTGR	2 to 4 MW(electric)	TRISO	Helium	—	—
NuScale Power	NuScale Microreactor	HP	<20 MW(electric)	Metallic	Liquid metal	Liquid metal	10 years
Oklo	Aurora	SFR/HP	1.5 MW(electric)	Metallic	Sodium	—	10+ years
Radiant Nuclear	Kaleidos Battery	HTGR	1.2 MW(electric)	TRISO	Helium	Graphite	4 to 6 years
Ultra-Safe Nuclear	MicroModular Reactor	HTGR	5 MW(electric)/ 15 MW(thermal)	TRISO	Helium	Graphite	20 years
Westinghouse	eVINCI™	HP	1 to 5 MW(electric)	TRISO	Sodium	Graphite	3+ years
X-Energy[33]	Xe-Mobile	HTGR	7.4 MW(electric)/ 20 MW(thermal)	TRISO	Helium	Graphite	—
Nano Nuclear Energy Inc.	NANO Nuclear	FR	0.5 to 1 MW(electric)	—	—	—	10 years

*If openly reported.

information collected by International Atomic Energy Agency[12] (IAEA).

III. ECONOMIC VIABILITY

To date, no small nuclear designs have become commercially available. As a result, there are considerable uncertainties regarding their ability to compete economically with other forms of energy. To some degree, this uncertainty, along with regulatory gaps, has hampered the adoption of small nuclear reactors by utilities, commercial firms, and governments. Most of the extant research on the ability of small nuclear technologies to be commercially competitive focuses on their capital costs. A widely used approach in studies providing estimates of these costs for smaller nuclear reactors is to incorporate historical capital cost data from large nuclear builds and scale these down to match the power output of smaller nuclear projects. This technique, termed the top-down approach (TDA), generally results in capital cost estimates for small nuclear reactors that are significantly higher, on a per megawatt basis, than other low-carbon energy technologies. However, claims about the uneconomic nature of small and microreactors in these studies stem from the use of excessive capital costs for large NPPs and an incorrect application of scale economies, alongside uncertainty about economies of production. TDA studies begin with the costs of large NPPs in order to estimate the capital costs of small nuclear designs. A key source of uncertainties about the competitiveness of new smaller nuclear designs is the extent to which they will exhibit the relatively high capital costs, excessive construction times, and excessive lead times that have been cited for large nuclear power facilities for some time, together with the potential for adoption in volumes that attain economies of production.[19–22] These considerations have complicated public perception and increased investor hesitancy over recent decades,[23] and by extension, have led many to question the economic viability of small nuclear facilities.[24]

In addition to the use of excessive capital costs for large NPPs in TDA studies of small nuclear technologies, another issue is the use of scaling factors to adjust NPP cost estimates to account for the significantly smaller power output of small nuclear designs. Where some design parameters of a new nuclear design are known, the costs of these system components can be compared to the costs of existing nuclear builds using scaling factors, detailed by the Energy Economic Data Base,[25] to scale the known costs up or down to match the size of the new project under consideration. However, this general scaling methodology is strictly applicable to cost estimations across essentially similar designs for which there are no significant differences other than power output (see, for example Refs. 26 and 27). The design differences between traditional, large NPPs and new designs for SMRs and microreactors are, however, significant enough that using scaling factors from the costs of large NPPs is insufficient to provide accurate capital cost estimates, even for those classified as pressurized water reactor (PWR) designs being developed for near-term deployment.

An alternative approach to capital cost estimation for new nuclear designs is the bottom-up approach (BUA). This is more data intensive and utilizes specific cost data on a component-by-component basis for a given new nuclear design. By doing so, this approach accounts for the specific characteristics, design simplifications, and reduced componentry of new small nuclear reactor designs. Incorporating unit prices for the specific components to be used in new nuclear designs, the BUA methodology “gives better cost estimations than TDA when it can be applied” as noted by Berbey et al.[28] This approach and its application to microreactor designs is reviewed in Sec. III.A.

III.A. BUA Assessment

As an alternative approach to the top-down methodology used in the studies cited previously, more accurate cost estimates can be obtained by a BUA when sufficient information is available. In these studies, capital cost estimates are obtained by detailing the required components for reactor construction, delivery, and installation of small reactor designs, with appropriate scaling factors applied to these component costs to account for their reduced size in small reactor designs. This approach is analogous to several studies on cost estimation for new advanced designs of large NPPs in which elements and component costs of existing nuclear builds are compared to systems and components of new advanced reactor designs in order to assess the overnight costs of nuclear technologies (see, for example, Refs. 27 through 31). For conventional NPPs, the Gen IV Economic Modeling Working Group guidelines specify nine general code of accounts (COA) categories, with six of these consisting of construction costs and the remaining three consisting of operating costs.[32,33] Two of these categories, Direct Construction Costs (Series 20) and Indirect Construction Costs (Series 30), are generally included in comparisons of overnight construction costs across nuclear technologies, and these are the pertinent categories for the discussion of overnight capital costs here.

While the studies cited previously use the COA framework to estimate the costs of new and advanced large NPP designs, a similar approach was used by Black et -al.[34] to estimate the direct and indirect capital costs of SMRs by comparing the number, size, and costs of SMR design elements with those of a standard PWR-12 nuclear reactor. The detailed direct and indirect cost components needed for all the systems of a standard PWR-12 reactor were compared to those of the NuScale SMR design. Many of the components of the PWR-12 are omitted in the NuScale design, and those that are present are of much smaller size. This study found that direct costs, including structures and improvements, turbine plant equipment, electric plant equipment, heat rejection systems, and miscellaneous plant equipment costs, were lower for the SMR design, both in absolute costs and on a per kilowatt basis, than for the PWR-12 design. Of particular note were the substantial savings for indirect capital costs for factory-constructed nuclear power modules due to lower field construction and indirect costs. Similar results were obtained in the bottom-up study of small reactors by Vegel and Quinn,[35] who used component costs for the Westinghouse AP1000 reactor to obtain capital cost estimates for the Westinghouse SMR, finding that direct capital costs would be relatively larger for small reactors than for large NPPs on a per kilowatt basis, but that indirect, contingency, and owner’s costs would be significantly lower.

It is important to note that some bottom-up estimates for SMRs are possible because their designs have matured sufficiently so that the componentry and materials can be identified and the costs estimated. The BUA for the capital cost estimation of microreactors is challenged by the lack of detail in actual designs that are publicly available. As with SMRs, uncertainty regarding the regulations and requirements for microreactors also present challenges. However, as noted by Carelli et al.,[36] the case for the economic viability of small reactors is enhanced because the much smaller size of new nuclear designs allows for solutions and efficiencies not available to large reactors. Indeed, the design differences between small reactors and large NPPs are highlighted by numerous studies that focus on reduced costs in small reactors relative to large NPPs (Refs. 21, 35, and 37 through 42). In line with such studies, modularization in design and manufacture, if produced at scale, can enable more efficient production and learning curve cost reductions and more off-site construction and attendant reductions in indirect capital costs and construction periods. Moreover, gains could be attained with shorter construction periods and reductions in financing costs, simplified designs resulting in reduced componentry needs, and integrated designs resulting in a smaller footprint and number of buildings. Christensen et al.[43] argue that planned safety features and smaller amounts of fuel allow for reductions in emergency planning zone size, activities, and required equipment for microreactor facilities due to the low probability of core damage and risk of off-site dose due to the smaller fuel cores in the microreactor designs reviewed. This is discussed more in Sec. VI.

While capital cost estimation is important, especially for nuclear technologies, such costs are only part of the factors needed to compare economic viability across different energy technologies. In Sec. III.B, important elements, such as capacity factor, production life, fuel costs, fueling intervals, costs of operation and maintenance, and other factors, are incorporated into estimates of the levelized cost of electricity (LCOE) for small nuclear reactors and microreactors. There are many advantages to these new nuclear designs that may dramatically improve estimates of their economic viability relative to other energy technologies.

III.B. Levelized Cost of Electricity

The studies cited earlier focus on the direct and indirect capital costs of the manufacture and construction of small nuclear electric power plants. A principal reason for this scrutiny is that these costs are relatively high and often represent a larger share of plant costs for nuclear power versus other electricity-generating technologies. In order to compare economic competitiveness across energy technologies, a broader metric, the LCOE, is used to compare the costs of energy production over lifetime production horizons across technologies. The fundamental factors in LCOE calculations include direct and indirect capital costs, financing costs and discount rate, capacity factor, the costs of fuel and nonfuel operations, maintenance costs, production period, and decommissioning costs. Each of these factors can vary significantly across technologies. This long-term comparison is especially important for nuclear power where capital costs are relatively higher than for other technologies.

One reason for the relatively high overnight costs for nuclear reactors is the quality requirements for specialized materials, enhanced safety features, backup control, and other equipment, which lead to higher direct costs, especially in the United States. On a global basis, overnight costs for new nuclear builds are estimated to consist of about 70% direct costs and 30% indirect costs, but in the United States, nuclear plants have averaged about 48% direct costs and 52% indirect costs over the past several decades.[44] In this regard, the findings of Vegel and Quinn[35] and Black et al.[34] indicating lower energy capital costs per kilowatt for small reactor designs relative to large NPPs are especially significant for indirect cost categories.

In addition to overnight costs, the cost of financing is an important driver of LCOE estimates for new power plants. This is especially the case with nuclear plants, where overnight and financing costs account for approximately 60% of LCOE (Ref. 44). For nuclear plants, total capital costs are strongly influenced by the length of the construction period due to attendant construction loan escalation.[45] For small nuclear designs, therefore, the extent of modularization and the related effects on reducing direct and indirect capital costs, as well reducing the length of both the construction period and financing horizon, can have significant effects on increasing the economic competitiveness of these smaller designs.

Other important factors in LCOE estimation are the capacity factor and the productive life of the generating facilities. For a given construction cost, a higher capacity factor will yield lower LCOE estimates because of the increase in kilowatts of electricity generated over the life of the plant. It is important to note that capacity factor measurements vary considerably across technologies. Nuclear power, for example, has the highest capacity factor of any electrical generation technology in the United States, averaging 93.5% on an annual basis compared to 57% for natural gas combined cycle, 48% for coal, 39% for conventional hydropower, 35% for wind, and 25% for solar photovoltaic.[46] As a result, the relatively greater role of capital and financing costs in determining the LCOE for nuclear power may be partly offset by the proportionally greater electricity output from these facilities. One issue for small nuclear designs is the extent to which future grid mixes incorporate load-following, thermal energy storage, or other measures to periodically reduce power output. As discussed later, the resulting reduction in capacity factor will increase LCOE estimates but may also increase overall revenue.

Along with capacity factor, another important factor is the role that operational horizons play in LCOE calculations. Historically, nuclear power facilities have relatively long operational periods, as evidenced by the recent extension of operating licenses by the NRC to over 85 large NPP facilities from 40 to 60 years.[47] This compares to operational horizon estimates of approximately 20 to 25 years for wind and solar facilities, approximately 20 years for combined-cycle gas turbines, and approximately 40 years for coal-fired power plants.[48] During these time periods, periodic capital expenditures are likely to be needed, but these estimates are generally taken to be the time horizon before major refurbishment or repowering projects are undertaken. As with large NPPs, relatively long operational horizons are anticipated for SMRs and microreactors, with similar downward pressure on LCOE estimates for these energy technologies.

Last, the costs of operations and maintenance (O&M) and fuel costs are also critical to LCOE estimations. Fixed O&M costs are generally higher for nuclear than fossil alternatives, due in large part to higher costs per kilowatt year for cooling systems, O&M personnel, and waste management. However, nuclear has lower variable O&M (VO&M) costs than most other utility-sized generating technologies using fossil energy. While these costs contribute relatively little to LCOE estimates for nuclear, their larger share in the operating costs of fossil technologies increases their LCOE estimates. The anticipated small share of VO&M costs for small reactor designs leads to similar effects for LCOE estimates for this technology.

As with VO&M costs, fuel costs for NPPs are lower in LCOE estimations than for coal-fired and natural gas–fired plants because these costs are measured on the basis of dollars per megawatt hour of electricity produced. For nuclear power, the amount of electricity produced per unit of uranium is much higher than the per unit energy output from coal or natural gas. As a result, fuel costs represent a much lower share of total generating costs than for fossil fuel energy facilities,[49] meaning that nuclear generating costs are much less sensitive to fuel price volatility than for coal or natural gas. For example, a recent Nuclear Energy Institute (NEI) study notes that a doubling of fuel cost will result in an increase in generation costs by 10% for nuclear, but a similar doubling of fuel costs will increase the generation costs by 32% for coal and 77% for natural gas.[50] For some small nuclear designs described in Sec. II, fuel costs are estimated to be low, in line with traditional nuclear facilities. However, fuel costs may well be relatively high for some microreactor designs using HALEU or other fuels that are costly to fabricate. As noted in a recent MIT report, these microreactor designs may find it difficult to compete economically with other energy technologies, whereas designs using relatively inexpensive fuels, such as uranium oxide with 5% LEU, are better suited for near-term commercial deployment.[15]

An important consideration of using LCOE estimates is the market structure for electricity sales. In regulated markets in which electricity prices are stable for extended periods, LCOE is a useful rubric to estimate the economic viability of new energy technologies. In such markets, LCOE estimates for large nuclear facilities are disadvantaged by the relatively high capital costs and long construction, with attendant increases in financing costs and risk. On the other hand, the high-capacity factors, low O&M and fuel costs, low fuel price volatility, and long operational lifetime all serve to decrease the competitive disadvantage often claimed for large nuclear facilities. For new smaller nuclear reactors, these same features, along with lower capital costs and reduced construction times and financing periods relative to large NPPs, further reduce LCOE estimates. However, using LCOE estimates as a rubric for economic viability is less appropriate in other market structures. In restructured and competitive wholesale energy markets, for example, the ability to reduce power output during periods of low electric prices and increase output when prices are high is a key component of maximizing revenue from power sales. As noted earlier, this reduction in the capacity factor of new reactors will increase LCOE estimates while at the same time also potentially increasing the profitability of employing new reactor designs.

III.C. Microreactor Cost Estimations

Given the recent development of microreactor designs, few bottom-up studies of microreactor costs are available. In one such study by the NEI (Ref. 51), a 10-MW(electric) reactor plant was referenced based on proprietary data from several microreactor developers. This reference microreactor utilizes two, co-located 5-MW(electric) reactors with a 40-year plant life, 10-year core life, and 95% capacity factor. Overnight capital costs, O&M costs, fuel costs, decommissioning costs, and financing costs for different types of owners, such as investor-owned and publicly owned utilities, over a 15-year debt term are all estimated for the specified design. For the first-of-a-kind (FOAK) microreactors of similar configurations, this study estimates levelized costs between \$0.14 and \$0.41/kWh (equivalently, \$140 and \$410/MWh). This study notes that cost reductions are likely as more units are produced, and that microreactors are expected to follow learning rates similar to those in manufacturing industries, where learning rates of 15% to 20% are evidenced, as in an analysis by the U.S. Environmental Protection Agency.[52] For this NEI study, however, more conservative learning rates of 5% to 15% were applied to capital costs after the first 50 units are manufactured. It is also noted that fuel costs and O&M costs are likely to decline as the industry matures. For fuel costs, the potential for decline is debatable if SMRs and microreactors are adopted in large volumes. Changes in fuel costs and O&M costs, however, are not included in the LCOE estimates for the NEI study. For N'th-of-a- kind (NOAK) microreactor units of the specified design, this study estimates a LCOE range of \$0.09 to \$0.33/kWh (\$90 to \$330/MWh). The relatively wide range of these LCOE estimates results from variations in the sample designs, site and transportation conditions, and learning curve assumptions.

A BUA to cost estimation for microreactors was performed by Abou-Jaoude et al.[53] for the Idaho National Laboratory (INL). To estimate capital costs, this research employed the Gen IV COA framework to incorporate the design features of a microreactor in publicly available literature, the Design A' HP reactor designed at Los Alamos National Laboratory. An important innovation in this study is the modification of some of the Gen IV COA to better fit with the microreactor design. The capital costs of this representative microreactor were estimated by employing scaling algorithms to adapt elements and their associated costs. The LCOE estimates were also estimated by using estimated O&M costs, fuel costs, and financing costs. In detailing the important elements of the microreactor LCOE, this INL study found that over half of the contributions to the LCOE of this microreactor design stem from direct capital costs, as is consistent with studies on large NPPs and SMRs (see, for example, Ref. 34). The second largest contributor to the microreactor LCOE is the initial fuel load.

After identifying the major drivers of microreactor LCOE, the INL study modified the design of the microreactor to reduce costs through the creation of a hypothetical new design. Design changes were considered for the reactor size, increasing from 5 to 8 MW(thermal), as well as the neutron spectrum, fissile inventory, plant lifetime, and refueling interval. In addition to the reactor design and operation, other changes were considered in the reflector characteristics, reactor building, instrumentation and control, and operations staffing. Costs were further reduced when going from FOAK to NOAK units by assuming a 15% learning rate for most cost components. Table II lists the major LCOE cost categories for the modified design (Design A).

TABLE II

Overall Summary of the Primary Cost Categories and Estimated LCOE for the Modified Design A for an 8-MW(thermal) Microreactor

Account Number	Cost Category	Estimated Cost (in Millions of U.S. Dollars)	Levelized Cost (MWh)
10	Project development	\$3	\$39
20	Direct costs	\$34	\$149
30	Indirect services	\$2	\$7
40	Operating staff recruitment, training, etc.	\$1	\$4
50	Capitalized supplementary costs, including initial fuel	\$13	\$55
60	Capitalized financial costs	\$2	\$24
70	Annualized O&M costs	\$1	\$39
80	Annualized fuel costs	\$2	\$83
		LCOE:	\$363

This LCOE estimate is within the $140 to $410/MWh range for FOAK microreactors estimated by the NEI (Ref. 50), as noted previously, but higher than the NEI estimate of $90 to $330/MWh for NOAK units. While these costs would limit the economic viability of microreactors in some markets, they indicate that microreactors can be competitive in other markets. As noted by the NEI (Ref. 50) study, initial microreactor units are likely to be competitive in remote markets as a replacement for expensive diesel fuels. This is illustrated by the findings of microreactor studies by the University of Alaska[54,55] for the following electricity costs for different segments of Alaska. For small, rural Alaskan communities, prices range from $350 to $600/MWh, with an average of $520/MWh. For Alaska Rural Hub communities, prices range from $170 to $480/MWh. With sufficient multiples of similar reactor designs deployed, learning curve reductions in capital costs, fuel, and O&M could make additional markets economically viable.[52] It should be noted, however, that the cost competitiveness of microreactors with other energy sources is only one element in a multidimensional energy development process. Additional value elements are important to consider in specific markets in which other factors, such as resiliency, ability to pair with renewables, capability to integrate with microgrids and other distributed energy systems, and other market characteristics, are important. These are further explored in Secs. IV and V.

IV. PROSPECTIVE PROFILE MARKETS, MICROREACTOR DESIGN FEATURES, AND COMPLEMENTARY TECHNOLOGIES

To shed light on specific prospective markets, potential microreactor uses were grouped into five global profile markets including: Isolated Operations, Distributed Energy, Resilient Urban, Disaster Relief, and Marine Propulsion.[3] Depending on the end use of the microreactor, different design features become prominent, for example, the right sizing for the location, modularity to support multiple unit deployment, mobility and transportability, coproduction of electricity and heat, reliability considerations, cost competitiveness, ability to start up without off-site power, flexibility of the power conversion system, long refueling cycles, need for minimal onsite facilities, and resilience to external events. Depending on the technical requirement, certain designs may be preferred. For example, in cogeneration applications, a HTGR could support higher temperature outputs. Applications requiring long periods between refueling could be best supported by microreactors using longer-lived HALEU fuels.

In addition to the reactor design features, complementary technologies coming from nonnuclear sectors are also needed to support the integration of microreactors into different profile markets, including

1. *isolated operations*: remote operation technologies (e.g., remote mining centers)
2. *distributed energy*: minigrids and microgrids to connect with renewables and storage
3. *resilient urban*: secure embedded intelligence to integrate with applications
4. *disaster relief*: mobile applications for critical services (e.g., desalination)
5. *marine propulsion*: ship-borne power conversion systems.

The five profile markets are detailed here along with potential complementary technologies in microreactor deployment, other low-carbon alternatives, and gaps requiring further innovations.

The first profile market is Isolated Operations, defined as high-value facilities and operations, typically government or industry owned, preferring 100% standalone operations or backup coverage for critical loads. Microreactors could operate semi-autonomously to support remote applications with electric and heat applications. Several industries are currently considering the use of remote operating centers (ROCs) for mining, military installations, federal facilities, data centers, university campuses, and other operations favoring energy self-sufficiency and improved energy resilience. Semi-autonomously operated microreactors powering remote operations have the potential for improved economics and to address certain aspects of personnel expertise shortages, assuming technical and regulatory challenges are overcome.[3]

In Isolated Operations, the core elements of a ROC include gathering, validating, managing, and reporting real-time and near-real-time operational data, analyzing the data and extracting meaningful information from it, and finally, using it for decision making for business operations.[56] The technologies that make ROCs possible include 5G for networking across the internet-of-things ecosystem by allowing rapid and secure transmission of vast amounts of data in real time. Augmented and virtual reality technology are used for visualizing and analyzing operations. Sensors generate data on various activities, network systems relay data from the operations site to the remote center, and supervisory control and data acquisition systems support data processing, data security, feedback loop optimization, and data analysis. These technologies are actively under development by industry for nonnuclear applications (e.g., data centers, remote mining). Initial microreactor deployments (2020 to 2030) will be less dependent upon ROC technologies that are still emerging. Deployments (2030 to 2035 timeframe) in isolated locations would benefit from the learning in other industries as well as infrastructure upgrades (e.g., wireless coverage). Future reactor designs include advanced digital technology and risk-informing cyber security for defensive measures. However, no matter how much technology is packed into ROCs, human engagement is expected through experts and stakeholders accessing data and support decision making. The level of isolation relates choices, including social or regulatory factors.[56]

The second profile market is Distributed Energy, which is defined as consisting of less capital-intensive users, including residences, businesses, municipal facilities, and local infrastructures (water, sanitation, and communications), requiring reliable energy sources. Microreactors could be integrated on a distributed electrical system including renewable energy and energy storage on microgrids and minigrids. Uses include electricity and heat applications[56] where infrastructure is present (e.g., district heating, desalination, and biomass drying). The use cases related to Distributed Energy profile markets include small rural communities, rural hub communities, and islands.[3] Additional applications in urban distribution systems are covered later in this section.

In Distributed Energy applications, difficulties have been seen in Indonesia and India when connecting minigrids to main grids.[57] In this situation, many minigrids have been abandoned due to their higher costs than the regulated tariffs provided by the main grid. However, minigrids are seen to operate more reliably. As a result, many customers choose to pay more to use the reliable minigrid.[57] Microreactors designed for high flexibility could bridge the grids by increasing energy production while strengthening grid reliability and helping to balance net loads. SMRs (including microreactors) could provide significant benefits for microgrid applications due to their ability to meet various power requirements and to compensate for intermittency associated with variable energy resources, which can also reduce the need for energy storage. Studies are currently being conducted on microgrids using microreactors to optimize cost and emission reductions.[58] In addition to electrical power, SMRs and microreactors could also provide thermal power for district heating, desalination, or other process heat applications.[59]

The third profile market is the Resilient Urban model, defined as emerging megacities (areas with 10 million or more inhabitants) in developing economies that lack the energy resources to provide for the basic energy needs for the population due to the lack of available land and infrastructure (transmission and distribution) and the capacity to reliably stand up to natural disasters. Over half of humanity—3.5 billion people—live in cities today, and 6 billion are projected to live in cities in 2050, according to the United Nations Department of Economic and Social Affairs.[60] A large portion of these users either lack grid access or are served by unreliable grids according to the World Bank and the International Monetary Fund.[60] Microreactors deployed in the 2030 to 2050 timeframe could operate as components in embedded energy systems serving the needs of urban centers and megacities.[3]

For urban applications, researchers from MIT and INL have laid out a possible solution based on distributed nuclear energy co-located with end users that avoids the need for massive, centralized infrastructure, such as a national grid. The new energy source includes nuclear batteries enabled by advances in embedded intelligence[61] and adaptive manufacturing and materials.[62] The result is a small, flexible, plug-and-play nuclear energy system that could serve urban applications, including residential, commercial, and industrial energy needs, such as heat for chemical industries, biomass drying, biofuel and hydrogen production, paper manufacturing, food production, and other industries.[63] Early-stage capital investment for nuclear technologies, such as those described previously, is expected to grow due to strong government policies and corporate net-zero goals.[64]

The next profile market is Disaster Relief energy, defined as areas particularly susceptible to harm caused by natural disasters, including hurricanes and typhoons, wildfires, earthquakes, and floods. Such disasters are expected to affect the populations in low- to middle-income regions most severely, both in terms of deaths and widespread damage, where the infrastructure to protect and respond to such events is lacking.[65] Currently, emergency power is provided by portable generators fueled by gasoline, diesel, natural gas, or other sources (liquid-propane gas and biodiesel). Such generators are used in residences to run a range of appliances, such as lights, refrigerators, sump pumps, heaters, TVs, water purifiers, and air conditioners in emergency situations. These generators have an average running time of 10 to 12 h before needing to be resupplied with fuel. The mobile nature of microreactors could allow them to be deployed to provide power and heat either independently or in a microgrid. Designers are giving consideration to requirements to provide flexible operation of the microreactor on or off the grid (e.g., the capacity to start up the reactor without offsite power)[58] and complement intermittent energy sources. In some situations, they could even be predeployed prior to the onset of forecast events or as a rapid response after a natural disaster (e.g., hurricane season) or an environmental change resulting in resource scarcities (e.g., water for hydropower). In addition to providing critical power to needed stationary and mobile facilities, such as hospitals and communications centers, microreactors could be deployed to provide power for desalination, heating, and other critical needs.[3]

In Disaster Relief and emergency recovery, fossil fuel–based generators (diesel, natural gas) are the standard, but they have important drawbacks. Currently, most nongovernmental organizations still house and deploy traditional solutions, including diesel generators.[66] When diesel generators are used for extended periods, there is the need to store and supply large quantities of fuel that may be expensive and difficult to transport. In a net-zero economy, unless the carbon from these fuels can be abated, cleaner strategies are needed. One strategy is to use solar energy to provide fast and temporary power; however, the energy from the panels is not typically stored and ready to go when emergencies happen. There is also the challenge of transporting large solar systems to remote areas (e.g., mountains of Nepal), which a UK technology company, Renovagen, is working to solve with their Rapid Roll system. Unlike traditional solar panels, Rapid Roll panels roll up, allowing the solar panels to be unfurled like a carpet.[66]

According to the U.S. Strategic Capabilities Office, the microreactor concepts selected to proceed to final design in Project Pele will be required to operate within 3 days of delivery and to be safely removed in as few as 7 days.[16] Mobile military microreactors have been suggested as an alternative to diesel generators used to supply electricity because they could eliminate the need for the expensive and hazardous transport of diesel fuel to remote locations or forward operating bases.[67] Microreactors consist of a microreactor module, a power conversion module, and a control module. The modules would each require packaging in a 20-foot-long CONEX shipping container ready for air, sea, or ground transport. Transport systems could use shipment containers supporting dual purposes, including the conveyance of fresh fuel cores to disaster sites and for the recovery of the reactors with partially used fuel. These details are yet to be specified, but developers could benefit from studying industries that have improved economics through reusability (e.g., SpaceX reusable rocket).

Marine Propulsion energy represents the next profile market, defined as commercial marine transport, currently dependent on diesel or bunker fuel to generate electric power to propel ships. Microreactors could be a viable alternative to power commercial ships to cut emissions and remove the costly refueling infrastructure needed for liquid-based energy carriers. Microreactors could be optimally sized (power/shielding/weight) for stacking together to meet the scale of different sizes of vessels. Size standardization is needed to achieve economics in production and to meet high quality requirements, however industry could agree to produce a few standard sizes to fit different applications, much like batteries are sold today (i.e., AA, AAA, C, and D). The advantages of using a reactor include long refueling intervals, faster transit speeds, production of heat or cooling for cargo, faster turnaround times due to the elimination of refueling, reduced draught allowing increased cargo capacity, and no need to transport huge quantities of engine fuel.[3] The use of nuclear propulsion would require a specially trained crew, refueling stations at ports, and waste management capabilities to prevent or contain any potential nuclear releases.

In Marine Propulsion, recent proposals include fitting cargo ships and cruise vessels with 80-m-high “sails” or “wings” powered by wind energy, reportedly cutting emissions by as much as 90% compared with today’s vessels. These wings create a lifting force that allows wind to provide the propulsion. Alternative power is still needed from a diesel engine, batteries, or sustainable fuels for sailing into and out of ports and during unfavorable weather.[57] Gaining the full benefits from wind propulsion will require a new design of vessels (i.e., sailboat). For retrofitting existing vessels, smaller wings will be needed to cope with the vessel’s stability and structural limitations, netting potential gains of 10% to 30% efficiency.[57] The nuclear alternative would require a ship’s engine room to be retrofitted to accommodate one or more microreactors, depending on propulsion requirements, not unlike vessels such as the *NS Savannah* passenger/cargo ship.[3] The port refueling systems needed to support a nuclear commercial shipping fleet are yet to be specified.

V. MARKET ASSESSMENT AND DEPLOYMENT

Research on the deployment potential of microreactors builds upon studies used previously to assess SMRs. An earlier study, performed by the U.S. Department of Commerce,[68] was scoped from the vantage point of a SMR vendor country that could identify potential international export markets. Subsequent studies expanded the number of indicators considerably to evaluate IAEA member states for their domestic characteristics and feasibility for domestic SMR utilization. Two studies were performed by Solan et al.[69,70] for the IAEA. These studies identified 22 SMR indicators and incorporated a more rigorous scoring system. These three studies were followed by another study by Black et al.[71] that identified five necessary conditions required for SMR deployment. A more recent SMR assessment study was released by the IAEA (Ref. 72) specifying 18 indicators and detailing an assessment methodology for IAEA member states. The IAEA study found that member states with strong economies, a high reliance on fossil fuels, a large share of imported energy sources, sufficient grid capacity, high energy-consumption growth rates, and high levels of greenhouse gas emissions are likely to have good potential for both large NPP and SMR deployment.

An in-depth market assessment of microreactors using a similar assessment methodology was completed in 2021 by Shropshire et al.[3] for the INL. This study showed that while microreactors and SMRs share some similar characteristics, potential markets for microreactors are likely to be different from SMR markets. Capacity differences mean that, in general, SMRs will typically operate in grid-served electricity markets where the physical infrastructure can support onsite construction and operation of the reactors. Microreactors are more suited to smaller niche applications and off-grid markets for integration with renewable sources in distributed energy systems sited in locations where physical space is limited and/or the energy infrastructure is minimal. Off-grid uses will require that microreactors have cold-start capabilities to not be dependent on external power sources. While differences exist, some of the market conditions favorable to increased SMR demand are also likely to increase the market potential for microreactors. As a result, some of the indicators used in the IAEA report on SMRs were used for microreactor deployment in the INL study. However, in order to better capture the unique characteristics of microreactors, 12 additional indicators were developed to assess the global microreactor deployment potential in the 2030 to 2050 timeframe. Specific microreactor design characteristics were compared to the performance needs of a variety of market sectors, including localized electricity demand conditions, flexibility requirements for integrating with renewables, thermal outputs needed to support process heat applications, modularity, capacity for transport, price premiums for existing energy production, dispersed or limited electricity infrastructure, high risk of energy disruptions, limited space for large energy generation systems, and others.

An important contribution of the INL study was the recognition that many of the market characteristics of importance to the use of microreactors are more localized than those for SMRs. As a result, the study employed several use cases to assess more localized market characteristics, some of which were developed as part of this study and others employed in other recent microreactor research studies. These use cases describe a range of potential applications that highlight different capabilities, design features, and applications of microreactors, similar to what was outlined in the previous section. The INL study introduced the microreactor indicators to assess the characteristics most applicable to the use of microreactors in each use case scenario. As with previous studies on SMR deployment,[69–72] the scoring of countries for each indicator was done based on the decile ranking by country. Unlike the previous studies on SMR deployment that assigned equal weights across indicators, the INL study weighted the indicators distinctly in each use case to account for the differences in market features and microreactor characteristics applicable for each use case. Using the weighted scoring system, the types of localized markets with the greatest potential for microreactor deployment were identified. The matching of the microreactor deployment indicators with the use cases suggested that microreactors have greater potential where there is a need to reduce vulnerabilities due to climate change and natural disasters, to diversify the energy mix with electricity and heat, to be competitive in current local markets, to be adaptable, reliable, and secure, to be deployed within the constraints of local infrastructures and access to capital, and to provide cost-effective alternatives where energy price premiums from other sources exist.

These use cases are closely aligned with the smaller and more localized applications relevant to microreactors. To identify global markets with a larger and more inclusive demand for microreactors, five global market types were identified in the INL study by combining similar use cases into profile markets or test cases, each with a unique, consistent, and multidimensional set of attributes. For example, an Isolated Operations profile market was identified consisting of remote mining operations, military installations, federal facilities, and university campuses. To capture a different set of market attributes amenable for microreactors, a Distributed Energy profile market was identified consisting of small rural community, rural hub community, and island use cases. The remaining profile markets are identified as Resilient Urban Application, Marine Propulsion, and Disaster Relief.

For each of the profile markets, quantitative assessments were done across nuclear power and emerging nuclear countries based on the indicators and use cases being most coincident with the features and capabilities of microreactors. Based on these assessments, there is significant potential among a broad variety of these countries for microreactor deployment going forward, with such potential varying across profile markets and across countries. In the Isolated Operations profile market, countries that share characteristics such as having areas with limited energy access, high levels of damage due to natural disasters, and remote mining operations are ranked highly. Other highly ranked countries have relatively large numbers of government facilities and university campuses. In addition, having high levels of imported energy or reliance on fossil fuels are favorable for microreactor deployment in this market. In Distributed Energy profile market, countries with characteristics including dispersed energy, local energy price premiums, high reliance on energy imports, and the need to balance renewables led to increased rankings, especially for countries with several populated islands.

In many countries, the growth of urban centers due to migration from relatively rural areas to cities has created challenges for the delivery of energy to growing populations, especially in the peripheral areas at the cities' edges. These characteristics are captured in the Resilient Urban profile market where countries with emerging urban megacities and insufficient utilities are highly ranked. In addition, government facilities and military installations, often needing resilient and stable energy sources, are located on the periphery of these areas. Unlike other profile markets, integrating microreactors with renewables is not a key component here because of the lack of expected space for solar and wind facilities. The Disaster Relief profile market shares some of the characteristics of the Resilient Urban market in that the economic damage and number of internally displaced persons from natural disasters can increase in more densely populated areas and those with high levels of physical capital and weak infrastructures. Thus, while countries with large urban areas vulnerable to hazards rank highly in the Disaster Relief profile market, countries with several isolated population areas are also highly ranked in this profile market. In each scenario, microreactors have the potential to reduce the damage from these events both before and after their occurrence. The predeployment of microreactors in disaster-prone areas can increase energy supply and provide energy stability and resiliency prior to an event. They can also facilitate recovery in the aftermath of these events by providing rapid deployment of stable energy for recovery and communications.

The final profile market analyzed in the INL study is Marine Propulsion. The use of microreactors is well suited for marine propulsion for commercial marine vessels that require 40 MW or less power or for larger vessels, where several microreactors could be stacked together. In addition to the negative environmental consequences of using bunker fuel for virtually all commercial marine transport, the economics of using microreactors are enhanced by the increased availability of cargo space due to the removal of bunker fuel storage. Countries with high potential for microreactor deployment in marine transport are those with either very large ports capable of handling many ships, those with many smaller commercial ports, or those that serve as shipping hubs for other countries in their region.

The assessment of microreactor potential described earlier is a needed step toward evaluating the projected market demand for microreactors globally. In the INL study, this bottom-up evaluation matching the needs in different profile markets with the characteristics and applications of microreactors was combined with top-down projections of nuclear capacity additions. Given that there is considerable variability in future nuclear demand across countries, there is resulting heterogeneity across regions. To examine the country assessments on a regional basis, this study used the global region groupings of the United Nations,[73] which is also used by the IAEA (Ref. 2) in projections for future nuclear energy capacity additions. These projections, which do not differentiate between nuclear technologies, show the greatest potential increase in nuclear capacity in Western Asia, Central and Eastern Asia, Southern Asia, and Eastern Europe as opposed to little increased capacity in North, South, and Latin America, the Caribbean, Europe (non-Eastern), Africa, and Oceania. The results for microreactors, however, based on the profile market analysis described previously, are quite different. Results from Shropshire et -al.,[3] shown in Figs. 1 and 2, provide the relative microreactor profile market scores by region.

These results are of interest in several respects. As with the IAEA nuclear projections, potential markets for microreactors could be strong across all the regions of Asia as well as Eastern Europe. However, unlike the IAEA's projections, microreactor markets could also be strong in other parts of Europe, Latin America, and Africa. In addition, there is some potential market demand for microreactors

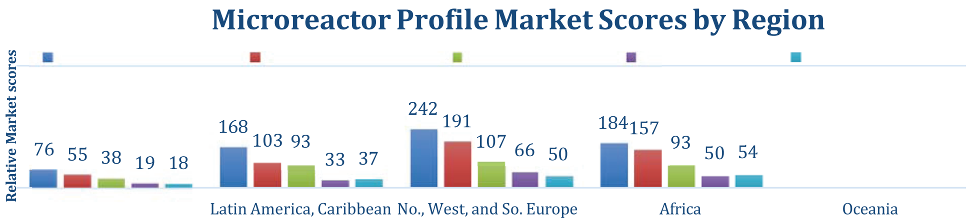

Fig. 1. Global regional comparative microreactor scores for Latin America; Caribbean; North, West, and Southern Europe; Africa; and Oceania.[3]

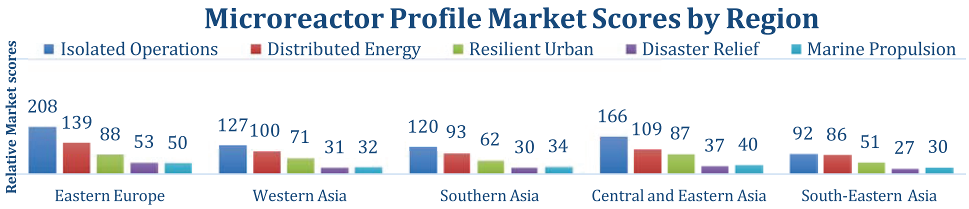

Fig. 2. Global regional comparative microreactor scores for Eastern Europe, Western Asia, Southern Asia, Central and Eastern Asia, and South-Eastern Asia.[3]

in North America. Oceania scores are zero since countries in the region do not use nuclear power or have not indicated interest in using nuclear power in the future. The results illustrated earlier also show the types of microreactor uses with the highest potential demand. Across the regions, the Isolated Operations and Distributed Energy profile markets show the most potential. In these markets, the ability of microreactors to be transported to areas with limited access and infrastructure and to be cost competitive with diesel generators, as well as having the ability to operate with low levels of personnel, be grid independent, provide highly resilient power for critical loads, have high-capacity factors and long refueling cycles, and other features provide the greatest ability for microreactors to be a part of low-carbon energy strategies going forward. An important factor in the ability of microreactors to penetrate given markets is the cost of energy alternatives. The price of existing energy sources in isolated markets is discussed in Sec. III.C. The respective cost targets based on profile markets in North America are provided in Table 19 in Shropshire et al.[3] Target costs range from <\$0.60/kWh for initial government uses, <\$0.50/kWh for Isolated Operations, <\$0.35/kWh for Distributed Energy, and <\$0.20/kWh for the Resilient Urban, Marine Propulsion, and Disaster Relief profile markets.

VI. REGULATORY-INSTITUTIONAL CONSIDERATIONS

As microreactor design development continues in a period of intense competition, the concept of very small reactors is not novel. Mobile reactors were commissioned in the 1960s and 1970s and then used for a radar station in Greenland and on a ship to power operations in the Panama Canal, among other installations.[8] As noted earlier, today's designs are being considered in the context of changes in fuel types, sensors, electronics, materials, and safety systems. With the newer designs that incorporate the planned, favorable attributes of the technology changes (described in other sections of this paper), reactor vendors are seeking regulatory change in terms of smaller or no physical containment, off-site emergency planning requirements, fewer operators, fewer armed security responders, and reduced equipment reliability requirements, as indicated by the NEI and the Union of Concerned Scientists.[50,74] It bears noting that the diversity of designs can be expected to translate in such a way that not all versions will include similar features. Given this, care should be exercised in generalized statements about safety, security, and safeguards. Expected gains could manifest quite differently across the international spectrum of designs and quality.

Questions, in turn, have been raised about new rulemaking and institutional capabilities pertaining to the technology and fuel characteristics, as well as the associated processes and their uses. An aim of this paper is to highlight the known aspects of the technology and areas under development. Design choices have considerable regulatory implications based on the direction that is adopted in the preliminary design. In line with this, it is important to indicate elements in the regulatory context that are pivotal for decision making.

Currently, microreactor technology is generally understood to incorporate passive systems and inherent characteristics in order to control power and heat removal.[10] Industry planning broadly anticipates design features such as passive cooling using natural forces to transfer decay heat,[50] accident-tolerant fuel, small thermal power outputs, strongly negative temperature coefficients of reactivity, and high thermal capacity of graphite structures.[3,14] Such conditions deviate from current requirements, warranting new levels of scrutiny and guidance.

Today's conventional fleet of nuclear reactors consists primarily of light water moderated and cooled reactor types, representing nearly 90% of the global commercial fleet[75] and the majority of regulators' experience. Distinct from the LWR design, microreactor technology designs are increasingly focusing on the demands of non-LWRs and nonaqueous coolants,[12] as well as fuel differences noted earlier. Such newer designs may be more suited for load-following, black-start capabilities, and transportability. More automated control systems and altered staffing sizes are also noted.[3] For commercial licensing, such adaptations will require regulatory capacity building and explicit review, as regulators like the NRC have not typically addressed these areas.[76] The design certification experience for conventional LWRs has already revealed challenges in evaluating generic seismic design loads for site locations such as those represented by potential siting in the Eastern United States.[29] For microreactors, the range of potential applications is even more varied at the design stage.[3]

An impediment for current regulatory assessments is the limited availability of operational data. Relevant data could be leveraged from systems and technologies that are utilized in nonnuclear facilities, including that for HPs, supercritical CO_2, and additional components.[3,77] However, variations in the operating conditions will still require attention in risk assessments[3,78] and explicit consideration of non-LWR designs.

Another area that requires regulatory-institutional consideration is the shipment of microreactors with fuel intact versus separate fuel transport and assembly on site. The choice introduces additional questions about transport requirements, cask options, export, and nonproliferation. Large-scale transport of HALEU fuel up to 19.75% enrichment, for instance, is not common and will require that additional security, safety, and safeguards be addressed.[3] Material control and accounting of the fuel will require review of the requirements for qualifications to ensure appropriate receipt, possession, inspection, and storage.[79] Shipping and fuel transport packages will need to be developed, tested, and approved for new microreactor designs.[80] If prospective vendors are interested in the transport of a prefueled mobile reactor from site to site with disaster response efforts, then multilocational considerations will require additional regulatory review.

Going further, adaptations will be needed for the unique operational lifecycle and components of microreactors. Specific to the operating lifecycle, some microreactor designs anticipate operations for at least 10 years prior to refueling, while others may extend to 20 years[77] or the operational end of life. This compares to average refueling for existing NPPs in the United States of every 18 months. Such changes in the fueling and the eventual decommissioning process present new questions about regulatory and institutional readiness. Novel equipment that has not been previously manufactured or which has not been used by the nuclear industry will also require new codes and standards for equipment performance, qualifications, and testing requirements.[77]

Siting plus O&M are also expected to differ from NPPs and SMRs. Microreactors could potentially be sited in remote, off-grid locations or near population centers. Assumptions about automation may entail information acquisition through sensing, to the down selection of options and decisions, through to action implementation.[81,82] The extent to which automation occurs introduces questions about the design of control rooms, the amount and type of staffing, surveillance, maintenance, and inspections/inspectors, together with the levels of safety and security thresholds, with implications for locations, uses, and costs, as noted earlier.[3] Choices about semiautonomous or autonomous use, for example, will require cyber risk considerations.[83] Safety, security, and safeguards will be critical in all settings, yet the elements of the risk profiles will differ.

Specific to natural hazard preparedness, microreactors have the potential for underground installation that could insulate them from above-ground hazards, including tornadoes and hurricanes, but not below-ground hazards. Due to the small nuclear material quantities in the reactor, potential radiation releases may be less than current NPPs. However, such releases may still occur underground with impacts, for example, to water. Depending on site selection and system hardening, subsurface siting does not minimize all possible natural hazard effects, such as those from flooding, seismicity, etc.

Turning to physical security and access, the compactness of the smaller reactor introduces new challenges for inspections, operations, and maintenance. Defense-in-depth analysis and monitoring will need to be factored for such modified needs.[3] Terrorism, vandalism, and nonproliferation, along with rapid response capability from operational teams and external impact assessments, will also need to be reconsidered.[3] In the case of aircraft impact assessments, for example, the underground siting of microreactors could minimize but not eliminate impacts. Critical qualitative assessments of security and access should be done early in the decision analysis process and throughout the reactor and fuel life cycles.[3]

Looking next at emergency planning, a reduction in zone size and distances required to meet dose-based regulatory criteria are areas for study, given the smaller reactor footprint and technology changes.[3] In addition to module size being a factor, the amount of radiation that could be released from a plant depends on the quantity of modules for a reactor and their interactions during an event, the magnitude of the event (e.g., earthquake, flooding, or sabotage), plus the status of the spent fuel storage.[74] Opponents of zone-size reductions will note support hinges on models and assumptions that have not yet been tested.[74] This is an area of study and rulemaking that remains unsettled. In the meantime, international guidance on emergency planning zones indicates that a radius of 5 to 30 km is warranted for reactors of 100 to 1000+ MW(thermal), and for reactors that are 2 to 10 MW(thermal) or 10 to 100 MW(thermal), recommendations are 0.5 km and 0.5 to 5 km, respectively.[29]

In response to all these developments, changes are occurring in the regulatory playing field. The NRC and Canadian Nuclear Safety Commission (CSNC) signed a memorandum of cooperation in 2019 that allows greater sharing of scientific information to support reviews of advanced reactor technology.[84] The CSNC also signed agreements for cooperation or information sharing with its nuclear regulatory counterparts in the United Kingdom, Japan, Switzerland, and China. Such cooperation can raise questions about the compromising of knowledge or sovereignty. In the case of sovereignty, final determinations on licensing lie with the local regulator.

Further to global developments, revisions may be needed for international agreements on transport, security, safeguards, and safety to address microreactor technology. The Convention for the Physical Protection of Nuclear Material, Nuclear Non-Proliferation Treaty, IAEA safeguards, and bilateral nuclear cooperation agreements are among the agreements that may require updating,[3] as well as other accords, like the Law of the Sea.

Taking these points of distinction for microreactors together, analysts of deployment will want to account for domestic regulatory and institutional capabilities. Key questions for consideration include: Is a nuclear regulatory agency in place and expert in advanced nuclear technology? To what extent are operator capabilities primed for the distinct differences of the new technology? Is there a domestic nuclear fuel program? Whether microreactors are imported or domestically produced, what transport mechanisms are in place? In addition, the level of cross learning that occurs among regulators, industry, laboratories, and universities will be a factor.

VII. DISCUSSION

This paper has challenged several findings related to nuclear power based on the current literature. Several areas of differentiation were established between microreactors and traditional NPPs and SMRs, including the following:

1. With respect to markets, the literature has considered SMRs as smaller versions of large NPPs, but primarily operating and competing in similar markets. This paper differentiates microreactors by their unique designs and capacity to operate in new markets as a replacement for diesel fuels and as a complement to small-scale variable power sources in distributed applications.

2. Specific to economics, the literature historically rests on economies of scale in power output, but SMRs and microreactors have shifted the focus toward economies of factory production and modularity to achieve cost reductions. This paper takes this a step further by considering the markets where microreactors could operate competitively and potential, new elements of "value" where decision makers place importance on additional measures, such as reliability and resiliency, flexibility, mobility, etc.

3. Achieving full market potential requires support from complementary technologies to bridge the gaps created by insufficient infrastructures, high penetration of intermittent energy sources, integration with users in remote applications, physical space limitations in marine applications, etc. This paper identifies ROCs, minigrids, and microgrids, plus secure embedded intelligence, as some of the key enabling technologies needed to bring microreactors into mainstream use within emerging markets.

4. In terms of regulatory and institutional issues, microreactors present novel conditions that are distinct from larger reactors. This paper highlighted the continued

need for regulatory guidance to inform designs and potential business decisions. This paper identified specific areas where regulators need data and sufficient designs to inform testing and rulemaking on safety, safeguards, and security.

VIII. CONCLUSIONS

This paper reviewed key areas in the state of knowledge for the international adoption of nuclear microreactors. The distinct characteristics of microreactors are highlighted, relative to large-scale nuclear reactors and SMRs, noting mobility and transportability, potential independence from the grid and semiautonomous operation, long refueling intervals, anticipated factory fabrication for the entire microreactor system, and a comparatively small footprint. These unique aspects are matched to an entirely new user set of electricity and heat products in localized and distributed applications. Complementary technologies coming from nonnuclear sectors (e.g., ROCs, minigrids and microgrids, secure embedded intelligence, mobile applications, and integration into ship-borne power conversion systems) are detailed to highlight prospective markets.

Drawing from earlier studies that assessed the deployment potential of SMRs and microreactors, this paper identified new areas to improve the analysis of microreactors. For example, rather than using static historic data, the focus is on evaluating future growth trends to understand a country's emerging energy needs. The methodology moves beyond indicators for benchmarking to create specialized indicators for microreactors to account for application-, region-, and subregion-specific conditions. Use cases for microreactors are outlined for a range of deployment conditions, including remote applications, mobile applications, small cogeneration applications, and urban and industrial applications. This paper underscores the importance of detailed local and regional data to move beyond country data and to describe the energy needs for local users that could be mapped to microreactor capabilities.

As microreactors alter the stereotype of traditional nuclear power, deployment will have its challenges and opportunities as a mature nuclear industry adapts to new regulatory and institutional considerations. Licensing, for example, must account for factory fabrication and shipping of fuel-intact reactors. Likewise, codes and standards will be needed for novel equipment. Hazard assessment and risk analysis must be adapted for new operational conditions, including below-ground installation and smaller emergency planning zones, as well as reactor and fuel transport. Adjustments may also be necessary for siting and oversight in remote areas, refueling, and decommissioning, as well as international agreements for transport, security, safeguards, and safety.

Findings from this study may provide country energy planners, private industry, and other stakeholders an improved capability to self-assess the potential use of microreactors as a subset of SMRs. Evaluations of technology, societal, and market conditions are important steps in decision making on energy strategies. Importantly, a full feasibility assessment should consider the regulatory capabilities, societal readiness, macroeconomics, infrastructure, public policies, financing, and unique country factors.

In looking forward, the outlined methodology and analysis can impact the future development of microreactors by zeroing in on the most viable uses of microreactors under specific local/regional conditions (e.g., microreactors used with minigrids and isolated operations in northern latitudes) to assess their highest potential market uses and the functional capabilities most needed in the designs. This is done to identify the conditions for the most technically feasible applications with achieved payback and to highlight key areas for regulatory and institutional address. Future research could examine the characteristics of these markets and their regulatory, institutional, and societal profiles, current suppliers and their market power, and the contractual relationships between existing suppliers and consumers.

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