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Can Distributed Nuclear Power Address Energy Resilience and Energy Poverty?

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Three major energy challenges are driving national and international energy decision making. First, the need to mitigate and adapt to climate change. Second, despite recent progress, many communities in both developed and developing countries remain in energy poverty or lack reliable, low-cost energy services. Finally, due to climate-amplified natural disasters and other threats, the reliability and resilience of energy systems is an increasing public concern. Existing distributed energy resources (DERs), especially solar photovoltaics and battery storage, are attempting to address each of these issues. However, more and faster progress is needed. Recent innovations in advanced nuclear designs could make nuclear power a distributed energy solution for the first time. As a dispatchable and resilient energy source, distributed nuclear could complement and accelerate the ongoing distributed energy revolution.

Although decarbonization imperatives are recognized, the role of distributed energy in addressing energy poverty and energy resilience is worth considering. Despite recent progress on electrification, much of the global population lacks access to affordable or reliable electricity. Fuel poverty is a complex problem that goes beyond just access, implicating socioeconomic issues that arise from insufficient energy services. More than half of the world’s poor are in rural areas, where they are vulnerable to the energy-poverty-climate nexus.\textsuperscript{1} Rural areas are hard to serve from an electric perspective as they require significant transmission infrastructure development to provide service, which is often too costly.

Meanwhile, emerging issues (such as the ongoing COVID-19 pandemic) have led to energy sector resilience being a policy concern. As keystone critical infrastructure, electricity supply is central to the operation of modern economies and social services. Energy disruptions are costly and dangerous. The 2003 blackout in North America impacted 50 million people and cost billions in economic damages. More recently, Puerto Rico’s power service has been severely disrupted by natural disasters, first by the 2017 Hurricane Maria and then by a January 2020 earthquake. In a review of electric outages between 2000 and 2016, natural hazards accounted for over 50%, intentional attack for 27%, system operations issues for 8%, and fuel supply emergency for 3%.\textsuperscript{2} Most disruptions were due to issues in transmission and distribution. Looking forward, climate change is expected to exacerbate natural hazards and drive additional system stress through air conditioning demand, while physical security, cyber security, and fuel supply threats grow.\textsuperscript{3}

In the last 20 years, rapid technological progress in solar photovoltaics, battery storage, and other renewable technologies led to the emergence of DERs.

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Distributed energy gets its name from the location on the power grid; units are often connected to the distribution portion of the grid, unlike traditional generation, which usually connects directly to transmission. DERs are characterized by their small size and scalability. Small enough to power a house, they scale up to power communities. They enable the operation of mini-grids and, with new technologies, may be grouped together as virtual power plants in larger, transmission-based wholesale markets.

Distributed energy addresses some of the primary public policy challenges of the electric industry. As carbon-free sources of energy, they contribute to climate mitigation (although distributed storage sometimes worsens carbon emissions). Their small scale means they could be deployed off-grid in areas without transmission grids, enabling them to address or even eradicate energy poverty. Further, distributed energy may increase the reliability and resilience of electric systems by diversifying supply and reducing dependence on specific transmission lines.

At the same time, distributed energy poses new challenges for electric grid operators. The primary distributed renewable, solar, is variable and constrained at higher latitudes and during certain seasons. Further, DERs have higher capital costs than utility-scale counterparts. Still, for areas without grid connections, distributed renewables are being combined with more traditional distributed systems—diesel generators—effectively.

**Utility Scale versus Distributed Nuclear**

Conventional utility-scale nuclear plants are the exact opposite of distributed renewable systems. Originally derived from technologies developed for naval propulsion, most are light-water reactors (LWRs) that use water to cool the reactor. To maximize reactor efficiency, they are sized as large as possible, with individual units usually greater than 1 GW-electric. Multi-unit nuclear power plants are some of the largest power plants in the world. Accordingly, large LWRs serve as a reliability and carbon-free backbone to global energy grids, providing approximately 10% of global electricity.

However, conventional reactors face significant constraints. LWRs must always pump water to cool the reactor, making them vulnerable to damage resulting from loss of offsite power, as occurred at Fukushima. Due to reactor physics, they have limited flexibility in power output, making them ill-suited to balance renewable energy grids of the future. They are also too large to serve isolated communities or even municipal utilities, with most operated by the largest utilities.

The most challenging factor for conventional reactors is economics, particularly initial capital costs. Although large LWRs have fuel efficiencies of scale, their large sizes have led to diseconomies of scale for individual construction projects. Alongside hydro facilities, conventional nuclear projects face the greatest risk of construction time and cost overruns for electric infrastructure. Due to rising costs during construction, they also face a risk of project cancellation. The recent issues with the AP1000 in the United States underscore these concerns; the Vogtle reactors were overbudget and the Summer reactors were cancelled. These economic challenges raise questions about the ability of nuclear power to scale to meet climate mitigation needs globally.

Microreactors, or micro-modular reactors (μMRs), are a radical departure from conventional nuclear designs. Derived from reactor designs originally investigated in the 1950s and 1960s, microreactor designs feature innovations inspired by the drawbacks of conventional designs. While a conventional reactor is 1 GW-electric or larger and a small modular reactor (SMR) is 50–300 MW-electric, μMRs are usually 10 MW-electric or less. This is equivalent in power output to 1–5 wind turbines or a small solar farm. At the extreme end, the Department of Energy and NASA are developing Kilopower for space exploration, with a size as low as 1 kW-electric.

New fuel types, fission cycles, passive safety features, and other operational changes could enable these ultra-small reactors to improve safety. Their small sizes decrease the heat to surface area of the reactor, allowing for passive cooling instead of the complex active cooling required for LWRs. By using new fuel forms and requiring vastly smaller amounts of uranium, off-site risks from a microreactor accident are limited. The designs used by small reactors are often termed as featuring inherent or passive safety.

Microreactor proposals may also feature improvements in fuel cycles, reduced water consumption, or less frequent refueling outages. In terms of energy supply, microreactors are likely to be especially resilient. Conventional nuclear reactors are already among the most resilient sources of energy supply. However, they face water supply limitations, a concern due to climate change. As microreactors use different processes, they generally do not require significant amounts of water. Further, microreactor designs often incorporate high-assay low-enriched uranium (HALEU) or other features that could reduce refueling frequency and costs.

Many vendors are now pursuing these designs. A report by the Nuclear Energy Institute (NEI) identifies at least 13 vendors in the United States, including traditional vendors like Westinghouse and BWXT. Notably, the existence of so many vendors is unusual for the nuclear industry, offering the promise of design...
and business model diversity necessary for financial innovation. An emerging industry participant, Oklo, just submitted a Combined License to the NRC, the first non-LWR design to do so. Initial commercial deployment of microreactors is possible by the mid-2020s.

Beyond revolutionizing commercial distributed energy, distributed nuclear might be a game changer for military applications. The US Army is currently investigating the use of mobile reactors to support ground operations, to reduce the risk of casualties from fuel convoys. DOD recently signed engineering contracts with 3 vendors. Mobile reactors could also serve as disaster response, with distributed nuclear replacing damaged power plants or bypassing damaged transmission lines.

Nevertheless, there are potential operational drawbacks to downsizing nuclear power. The greater ratio of surface area to reactivity means that activated materials may pose a greater issue, as well as a reduced number of neutrons decreasing fuel efficiency. Materials innovation and the use of HALEU could mitigate such challenges. More worryingly, the largest constraint for distributed nuclear remains one of the factors motivating their innovation: economics.

**Microreactor Economics**

Lower fuel efficiency and smaller capacity sizes mean microreactors are likely to be more expensive than utility-scale reactors, just like other DERs. Besides physical efficiencies, regulatory efficiencies related to siting, licensing, and operation also decrease as reactor size falls. To offset these losses, microreactor vendors aim to reduce construction risks and to target areas with the highest energy prices.

Economically, advanced reactor vendors, including SMR vendors, are attempting two methods to reduce the financial risk of constructing a nuclear unit. First, they intend to use modular construction, a technique pioneered by the shipbuilding industry, to harness factory-level economies of scale.

Second, by reducing the size of the reactor, vendors plan to reduce the absolute capital cost to build a demonstration project for a new design and follow-on commercial projects. A smaller project could reduce construction timelines and lower the risk of time overruns to cause cost overruns. Simplicity beats complexity. In the long run, smaller unit sizes for energy technologies have been shown to increase the rate of learning-by-doing. If construction risks decrease, the cost of capital generally declines. Smaller units may also reduce stress on supply chains, which was a cost headwind for past large-scale buildouts of nuclear.

Nevertheless, these two methods have yet to be demonstrated to reduce nuclear costs. SMRs may be able to harness these and other cost innovations to match or beat costs of large nuclear facilities. However, microreactors are still likely to have higher capital costs per MW and levelized costs per MWh, mirroring the economics of other DERs.

NEI’s report illustrates the economic situation for microreactors. Based on analysis of proposed designs and financing models, NEI estimated a first-of-a-kind (FOAK) facility could be built with a levelized cost of $140-410/MWh. Depending on the learning rate, an nth-of-a-kind (NOAK) facility might reach $100-$300/MWh. While not competitive with grid-based electricity, this may be competitive with diesel power for arctic communities, islands, remote industrial operations, and defense facilities.

**Competing with and Complementing Distributed Renewables**

At these prices, distributed nuclear may also be competitive with distributed renewable energy and storage technology. Lazard’s most recent levelized cost data indicate a cost of $160–$267/MWh for residential rooftop solar and $81–$170/MWh for commercial and industrial users. Distributed solar, along with small batteries, are increasingly the DER of choice for communities around the world. In the short term, renewable DERs are likely to be the greatest direct competitor with new microreactors. While FOAK microreactors are less likely to be competitive in many markets, they could be good choices for communities that have limited renewables resources, particularly in northern latitudes that many microreactor vendors are targeting.

Additionally, new nuclear designs may provide non-electricity coproducts, such as process heat, district heating, hydrogen, or even remote desalination. The first two are especially valuable for high-latITUDE locations. Microreactor designs promise dispatchable power, offsetting the solar variability issues that complicate distribution grid operations and supply of resilient power during blackouts. Unlike conventional nuclear, the fission cycles of some advanced reactors might allow core reactivity to change more often in a flexible manner. Microreactors may also be paired with on-site battery storage to maximize the economic value of their capacity. Molten salt reactors could integrate molten salt thermal storage.

Besides competition, proposed microreactors could complement distributed solar and storage. Oklo’s design features roof-mounted solar panels. With effective collaboration and planning, mini-grids enable early electrification efforts, energy access, and long-term development for isolated communities; microreactors might support other distributed energy sources in developing these initial mini-grids. As they do not rely on consistent fuel deliveries, they are not vulnerable to fuel price volatility or supply chain disruptions. They
could provide energy to off-grid locations that need electrification most, like Sub-Saharan Africa. Recent research has indicated that mixing firm electricity resources with variable renewables achieves least-cost decarbonized energy service, indicating the possibility of firm distributed nuclear doing so for micro-grids. 14

**Commercial and Regulatory Barriers**

If microreactors are to substantially contribute toward bolstering energy resilience and alleviating energy poverty, they have many barriers they must overcome. Industry, policymakers, consumers, and climate advocates all have a role in developing a conducive market and policy environment for these issues to be addressed.

Beyond questions of general economics, there are three primary commercial barriers to microreactors. First is the reduction of costs from FOAK to NOAK reactors. As with other energy technologies, future projects are expected to drive costs down as innovations and production economies of scale are achieved. The rate of this learning curve is critical to the eventual economic success of NOAK units. Second, NOAK reactors would need to shift from sophisticated, more price-agnostic initial customers like the military and industrial operations to rural communities more broadly. Municipal and rural utilities do not have the experience operating nuclear reactors. Build-own-operate models, which are not used by incumbent Western developers, may be critical for this (while also creating incentives to minimize project costs). Third, microreactor vendors must achieve each of these commercialization challenges while competing with other DERs and grid-delivered energy.

The economic barriers must be overcome at the same time as two major regulatory hurdles.

First, licensing reform is needed for vendors to demonstrate their safety case to nuclear regulators. In the US, nuclear safety licensing is prescriptive, meaning it defines specific technical requirements based on traditional light-water reactors. Recently passed legislation, the Nuclear Energy Innovation and Modernization Act, requires the NRC to embrace “performance-based, risk-informed, technology-inclusive” regulations. This shift to performance-based regulation requires regulatory work from NRC to ensure that it maintains a high level of safety. Exporting microreactors requires licensing in foreign countries, and countries with the greatest energy poverty issues often lack a nuclear regulator. International harmonization of nuclear licensing, namely international licensing or reciprocal licensing, is likely needed to open these markets.

Second, there are several regulatory and policy issues to using distributed nuclear in rural communities. Operationally, small communities and utilities do not have the knowledge or experience to integrate a reactor. To minimize costs, some microreactor vendors propose remote operation, which is currently prohibited by NRC regulations and raises cybersecurity risks. Distributed nuclear facilities face security and non-proliferation concerns. Many units with small amounts of radioactive materials could be an attractive terrorism or vandalism target. Technical innovations like putting reactors underground, safeguards-by-design, and other physical barriers could help. Still, these risks preclude deployment in areas with high instability, which often endure the most severe energy poverty. International cooperation must manage non-proliferation and security concerns as well as build the regulatory infrastructure needed for nuclear newcomer countries.

Sustainable development efforts to address electrification should continue to support distributed energy sources, while also fully considering how distributed nuclear would complement renewables and storage.

**DECLARATION OF INTERESTS**

A.O.G. is an employee of Nuclear Innovation Alliance, a non-profit think tank.

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Commentary

Energy Consumption of Cryptocurrencies Beyond Bitcoin

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Bitcoin’s energy hunger has triggered a passionate debate in academic literature as well as in the general public about the energy consumption of cryptocurrencies. Bitcoin is a digital currency based on a cryptographically secured distributed ledger and represents the first and best-known blockchain application. Its computationally intensive validation process called “mining” requires specific hardware and vast amounts of electricity to reach consensus about ownership and transactions. Depending on the methodology and assumptions, energy consumption estimates chart a wide range of results as depicted in Figure 1. The methodologies of the estimates have become more sophisticated over time, and yet, most studies have focused exclusively on Bitcoin and thereby ignored that more than 500 further mineable coins and tokens exist.1

Beyond Bitcoin

To estimate the energy consumption of cryptocurrencies beyond Bitcoin, we resort to a methodology proposed by Krause and Tolaymat2 that employs hash rates of cryptocurrency networks and suitable mining devices. Hash rates measure the processing power; they describe the number of attempts per second to solve a block in the so-called “proof-of-work” mining process. Table 1 lists the hash-rates of the top 20 mineable cryptocurrencies by market capitalization that account for more than 98% of the total market capitalization. These top 20 use 13 different proof-of-work algorithms. Bitcoin, for instance, uses the SHA-256 algorithm that allows for mining with highly specialized, ASIC-based devices, which are considerably more energy efficient than conventional graphic processing units (GPUs). GPUs are used, for instance, to mine Monero that prevents ASIC-based devices from its validation process.3 Table 1 lists the efficiency of mining devices that suit the respective algorithms. Dividing the network hash rates by efficiencies of mining devices yields the rated power of each network. Figure 2 illustrates the cumulative market capitalization and rated power of the top 20 cryptocurrencies: #1—Bitcoin—accounts for 2/3 of the total energy demand; #2–20 complement 1/3.

It is important to note that currencies with ASIC-resistant algorithms consume an overproportionate amount of energy in relation to their market capitalization.

Table 1

| Cryptocurrency | Market Cap | Hash-Rate (MH/s) | Efficacy (W/MH) | Rated Power (GW) |
|----------------|------------|------------------|-----------------|-----------------|
| Bitcoin        | 1           | 214,960,000,000  | 214,960,000,000 | 1.17             |
| Litecoin       | 2           | 176,250,000,000  | 176,250,000,000 | 1.05             |
| Ethereum       | 3           | 144,550,000,000  | 144,550,000,000 | 0.94             |
| Monero         | 4           | 112,050,000,000  | 112,050,000,000 | 0.82             |
| Bitcoin Cash   | 5           | 90,750,000,000   | 90,750,000,000  | 0.58             |
| Digicoin       | 6           | 78,450,000,000   | 78,450,000,000  | 0.50             |
| Zcash          | 7           | 66,150,000,000   | 66,150,000,000  | 0.41             |
| Dash           | 8           | 53,850,000,000   | 53,850,000,000  | 0.34             |
| Namecoin       | 9           | 41,550,000,000   | 41,550,000,000  | 0.27             |
| Peercoin       | 10          | 29,250,000,000   | 29,250,000,000  | 0.19             |

In absolute terms, the total energy consumption estimate in Figure 1 appears rather conservative. Alternative estimation methods (including, e.g., auxiliary losses in mining facilities) suggest that the actual energy consumption of Bitcoin might be higher: Digiconomist,4 for instance, derives 7.9 gigawatts (GW), and the Cambridge Bitcoin Electricity Consumption Index (CBECI)5 states 6.1 GW, whereas we estimate 4.3 GW (all estimates with a cutoff date of 03/27/2020;