Correction

CORE CONCEPTS

Correction for "Core Concept: Microgrids offer flexible energy generation, for a price," by Gayathri Vaidyanathan, which was first published April 24, 2018; 10.1073/pnas.1804507115 (*Proc Natl Acad Sci USA* 115:4298–4300).

The editors note that on page 4298, right column, last paragraph, line 6, "995 kilowatts" should have appeared as "995 kilowatt hours"; on page 4300, right column, third paragraph, line 11, "20 billion kilowatts" should have appeared as "20 billion kilowatt hours"; and in the next paragraph, line 4, "52,000 kilowatts" should have appeared as "52,000 kilowatt hours." The online version has been corrected.

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CORE CONCEPTS

Microgrids offer flexible energy generation, for a price

Gayathri Vaidyanathan, *Science Writer*

In the 1990s, University of Wisconsin researcher Robert Lasseter was working in an academic no-man's land. Lasseter was investigating small devices of less than 100 kilowatts called microturbines that were used in buildings as backup power generators. Some buildings had several of these devices, and Lasseter and his students wanted them to operate synchronously as one integrated power-generation source.

It was a big ask. The devices weren't designed to cooperate with each other. Link too many of them, and dangerous voltage and frequency fluctuations could crash the setup. After several years of research, the scientists designed hardware, called controllers, that could regulate the voltage and frequencies such that multiple generators and loads could be added seamlessly to form a simple power grid. They set up a proof-of-concept in Columbus, OH.

In 2002, Lasseter gave a talk at the Institute of Electrical and Electronics Engineers Power Engineering Society winter meeting titled, simply, "Microgrids," and laid out his vision. Microgrids should be able to operate independently, or in "islanded" mode, from the central grid, he said. The system should be modular so that new generation sources and loads can be added to the system without additional configuration. And in many cases, microgrids could be linked to the central grid, drawing or supplying power as needed from or to the larger system (1).

It was a brave new vision for electricity generation. For the past 150 years, electricity has been generated in large, centralized power plants and has travelled one-way through thousands of miles of high-voltage transmission lines into people's homes. North American consumers consider electricity delivered at 60 hertz and 110 volts to their sockets as more of a right than privilege. But doing so effectively requires impressive engineering to ensure that supply almost instantaneously matches demand and that voltage and frequency are precisely managed, notes Tom Jahns, a researcher at the Wisconsin Energy Institute at the University of Wisconsin–Madison.

Microgrids turn this system on its head, because the point of power generation becomes decentralized. These mini-utility grids contain all the basics of the grid, from power generation sources and transmission lines to controllers, energy-storage devices, and loads, but on a much smaller scale. They're increasingly powered by renewable energy. Electricity is stored in devices such as batteries and distributed to local loads. Microgrids, already in the pilot stage at several locales, could provide resilience for places such as Puerto Rico, which went almost completely dark after Hurricane Maria, and could one day make economic sense—if, that is, engineers can overcome technical hurdles and companies and policymakers can overcome regulatory ones.

A not-for-profit called Mlinda has installed about a dozen solar-powered microgrids, such as this one in Sahitoli in Jharkhand, India. Image courtesy of Mlinda.

Empowering Consumers

In Sonoma, CA, Stone Energy Farm, an organic farm and vineyard, runs on a complex microgrid that generates 461 kilowatts of energy from a mix of solar photovoltaics, a gas turbine, and fuel cells. The generated power is stored in batteries with a total capacity of 995 kilowatt hours. Setting up the microgrid was far from simple, says Jorge Elizondo, lead engineer at Heila Technologies, which helped build Stone Energy. Microgrids have not yet fully achieved Lasseter's vision of modularity, and most systems in the developed world require months of custom engineering, although Heila's mix of artificial intelligence and game theory has

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allowed for some degree of standardization. "You have a new device, in a typical microgrid, you have to rewrite a lot of rules to account for it," Elizondo says.

Initially, it was challenging to incorporate supply from thousands, potentially millions, of low-voltage microgrid sources into the high-voltage central grid. Each power generator in a microgrid—solar photovoltaics, for example—would have its own controllers for maintaining voltage and frequency oscillations and supply–demand uncertainties. The control devices would have to cooperate with each other.

In fact, most microgrids these days have hierarchies of controls. Primary controllers regulate voltage and frequencies of each generation device. Secondary controllers allow communication between primary controllers and devices, letting the microgrid function as a whole. Tertiary controllers enable the grid to respond to external signals, such as from electricity markets. Getting the multiple layers communicating can be expensive and challenging.

Complicating matters, conventional grids have protective devices that can detect abnormal, or faulty, currents and break the circuit to isolate a part of the system. Those devices do not work well in a microgrid, so new protection schemes have to be engineered.

Researchers and engineers have largely addressed these issues and are now studying the best ways to organize the future grid. Some big-data companies such as Cisco Systems, Inc. propose a highly centralized control system in which large computers manage the entire grid from command centers that make decisions and communicate them to local microgrids via the Internet. But much like the current grid, this architecture would be vulnerable to cyberattacks. There is a growing consensus that a distributed structure that splits decision making among various levels of control would be more robust, Jahns says. "Do you want the continuity of your electric power in your building to be dependent on how well the Internet is working on a given day?" he asks.

Another issue lies in devising optimization models used by utilities that decide how to match needs in real time and at low cost. These control algorithms would have to accommodate the added complexity of thousands of low-voltage inputs in the future. "The challenge of power systems is that demand and supply essentially have to instantaneously match all the time," says C. Lindsay Anderson, an assistant professor who is working on these models at the Department of Biological and Environmental Engineering at Cornell University. "It is a very precise problem."

Cost Versus Benefit

Even after the technical challenges are resolved, renewable energy microgrids aren't likely to be widely adopted in the United States without mitigating regulatory and economic roadblocks. The United States has a Renewable Portfolio Standard requiring 10% renewable energy generation by 2020 and 25% by 2025. Additionally, 30 states and the District of Columbia have standards requiring that a minimum share of electricity come from renewables. But state

In the village of Sahitoli, microgrids help power irrigation for planting crops. Image courtesy of Mlinda.

regulations were written for traditional utilities and do not address the idiosyncrasies of distributed energy projects. In some states or municipalities, selling electricity to multiple customers, or crossing a public right-of-way, automatically classifies the company as a "public utility"—hence triggering heavy regulations that private developers would rather not face.

Many states regulate the component technologies of a microgrid individually rather than the system as an integrated benefit, says Dirk van Ouwerkerk, lead partner for Anbaric Microgrid. Ideally, microgrids should be made a distinct regulatory category and be allowed to participate in the wholesale and retail electricity markets, he says. And the costs of interconnecting to a grid, which can be astronomical, should be borne equally by the microgrid company and the utility, he adds. "We are among the few [private companies] that are trying to develop microgrids and it's very hard," says van Ouwerkerk, whose company started developing microgrids in 2014. "These regulatory hurdles are formidable, and nowhere is there a solution in sight."

Some utilities, in their informal conversations with local regulators, resist decentralized power generation by private companies which, they believe, could eat into their profits or, even worse, destabilize the central grid. These may need a nudge from regulators. "You can have the best technology in the world, but it isn't worth anything if the regulatory or market conditions are such that it can't digest that kind of technology," Jahns says.

But a few progressive utilities are setting up their own microgrids as experiments in cleaner power. One is St. Louis-based Ameren Corp., which has built a utility-scale microgrid pilot in Champaign, IL, supplied by solar, wind, natural gas, and batteries. The microgrid is connected to the conventional grid but can also function in islanded mode, supplying 1 megawatt to customers who are willing to pay a premium for supply during outages.

Experts say that it is still unclear whether it makes economic sense for an electricity consumer—say a New Jersey resident who lost power during Hurricane Sandy in 2014—to take part in and pay a premium for a system that provides electric power redundancy. That resident has to believe that the present value of investing in the system would outweigh his or her financial loss from losing power for about a week if another hurricane were to hit, says Stephen Doig, managing director at the Rocky Mountain Institute. "I think the challenge here is there's a lot of incumbent tech and incumbent players," he says. "And until you can demonstrate unequivocally that the economics are better, it'll be tough for people to shift."

Developing-World Solutions

The economics make a little more sense in the developing world, particularly in Asia and Africa, where the central grid is either unavailable or unreliable. Microgrids in India, Indonesia, and Tanzania could serve 212 million people, according to an analysis by Allotrope Partners.

In the villages of Jharkhand in northeast India, power from the central grid is intermittent and the voltage unstable. Mlinda, a nongovernmental organization, recognized that a microgrid might help provide more reliable power. Beginning in 2016, it set up 25-kilowatt solar photovoltaic-plus-battery systems with a diesel generator backup in eight villages. The microgrids supply constant voltage 24 hours a day, says Vijay Bhaskar, country director for Mlinda.

But it wasn't cheap. Setting it up required $75,000 per village, a massive capital requirement in Indian currency. Mlinda sourced the money through grants, private equity, and debt. The microgrid power is three times as expensive as from the central grid. For the system to be commercially viable, it needs to operate at 85% capacity within 2 years, Bhaskar says. That can be a challenge if the community has never had consistent energy access. They may not know what to do with the electricity without an accompanying betterment of livelihood and commerce, he says. "It's not enough to just provide access to energy. It is important to address village development," he says. "That can happen only if you look at the livelihoods."

To have microgrid success in the developing world, Doig would like to see hardware standardized so that modular components could be manufactured in large-enough quantities and deployed quickly and cheaply (2). At present, a single company tends to develop, build, own and operate the microgrid assets in most nations. Having specialists responsible for each of these functions would improve efficiency and allow more projects to become investment ready, says Dan Schnitzer, cofounder of SparkMeter, a developer of microgrids in emerging markets whose main office is located in Washington, DC.

Once deployed, the grid needs to operate at 70% capacity at all times to be economically viable. The best way to achieve this target is by supplying commercial customers who require electricity during daytime when residential usage is low and solar generation is at its peak. After dark, the more expensive backup generation from batteries or diesel switches on. "If the only power that people draw is from 6 to 10 at night when it's dark, that's not a good customer segment," Doig says. By following such guidelines and building on the achievements of multiple pilot projects, Doig expects that in the next decade microgrids will flourish across sub-Saharan Africa.

Schnitzer of SparkMeter says that nations need clear regulations on whether private companies are allowed to build, own, and operate microgrids and supply electricity. Without clarity, there is a danger that utilities will expropriate projects, says Schnitzer. "In a lot of geographies, it's been a wild west kind of approach where a lot of developers are building their projects at risk," he says.

Puerto Rico Rebuilds

In Puerto Rico—reeling for months after Hurricane Maria caused widespread outages, though most customers now reportedly have power—coal-fired power plants supply almost all power. Energy entrepreneurs such as Tesla, Inc. founder Elon Musk have supplied solar-plus-battery microgrids to the island, but these will not be the sole solution, experts say. The Puerto Rico Electric Power Authority is now repairing the central grid using the services of American utilities to bring thermal power plants back online. In 2014, the Electric Power Authority supplied 3.5 million people with 20 billion kilowatt hours of power.

In comparison, the biggest solar-plus-battery microgrid facility Tesla has demonstrated so far, on the island of Kauai, has just 13 megawatts of solar generation and 52,000 kilowatt hours of battery storage capacity. Still, microgrids could be part of the solution in parts of the island the central grid does not reach, Doig says. Puerto Rico could even be a proof of principle for how distributed energy generation and the central grid can coexist in a large island in a manner that is cost efficient and resilient.

At the very least, microgrids likely would have helped Puerto Ricans regain power and basic functions more quickly. "I don't want to say that everything would be rosy if there were microgrids [in Puerto Rico]," says Jahns, "but I will go as far as saying, I think it would be a whole lot better than what it is."

1 Lasseter R, et al. (2002) Integration of distributed energy resources: The CERTS microgrid concept. Available at bnrg.eecs.berkeley.edu/~randy/Courses/CS294.F09/MicroGrid.pdf. Accessed March 15, 2018.

2 Carlin K, et al. (2017) Energy within reach: Growing the minigrid market in sub-Saharan Africa. Available at www.rmi.org/energy_within_reach. Accessed March 15, 2018.