TECHNOLOGY

MICROGRID MOMENTUM: BUILDING EFFICIENT, RESILIENT POWER

CENTER FOR CLIMATE AND ENERGY SOLUTIONS

Doug Vine
Center for Climate and Energy Solutions

Donna Attanasio
Ekundayo Shittu
George Washington University

March 2017

INTRODUCTION

When Hurricane Sandy cut off power to millions of homes and businesses in the Northeast, a few areas, mostly parts of universities, kept the lights on using their own power generation systems. This ability to sustain electricity service during widespread natural disasters is one reason for the growing interest in microgrids. But they offer other important benefits as well. By increasing efficiency, integrating renewables, and helping manage energy supply and demand, microgrids can reduce greenhouse gas emissions and save energy. For utilities, microgrids can ensure power reliability in remote areas. Microgrids also appeal to those who want to disconnect from utility bills.

In this paper, a microgrid **(Figure 1)** is defined as a relatively small, controllable power system composed of one or more generation units connected to nearby load that can be operated with, or independently from, the local distribution and bulk (i.e. high-voltage) transmission system, referred to as the "macrogrid" in this paper. Microgrids can run on renewables, natural gas-fueled combustion turbines, or emerging sources such as fuel cells or even small modular nuclear reactors. They can power critical facilities after a weather- or security-related outage to the broader grid, or be the main electricity source for a hospital, university, or neighborhood. Single-user microgrids, such as those that serve an industrial site or military base, have existed for decades. But the current interest includes systems that can better integrate generation resources and load, serve multiple users, and/or meet environmental or emergency response objectives.

Microgrids are not a traditional or typical infrastructure investment for utilities, nor has the existing electric power industry been structured to facilitate development of microgrids by non-utilities. This research paper seeks to identify financial and legal barriers to the development of microgrids and provide recommendations for overcoming them.

KEY TAKEAWAYS

- Microgrids currently provide a tiny fraction of U.S. electricity (about 1.6 gigawatts (GW) of installed microgrid capacity or less than 0.2 percent), but their capacity is expected to more than double in the next three years. Fueling interest in microgrids is their ability to improve resilience and reliability, increase efficiency, better manage electricity supply and demand, and reduce greenhouse gas emissions.
- Each microgrid's unique combination of power source, customer, geography, and market can make financing these projects a challenge. Financial feasibility studies, simulation modeling,

and public-private partnerships all could play a growing role in overcoming financial hurdles.

- States can play a key role in facilitating microgrid development. Most existing microgrid projects are concentrated in seven states: Alaska, California, Georgia, Maryland, New York, Oklahoma, and Texas. Some states, including California, Connecticut, Massachusetts, New Jersey, and New York, have created funding opportunities for microgrids. But most states lack even a legal definition of a microgrid, and regulatory and legal challenges can differ between and within states. States can assist project developers by providing funding, grants or low-cost loans to perform feasibility studies or to aid in demonstration and commercialization.
- A clearer legal framework is needed to define a microgrid, and set forth the rights and obligations of the microgrid owner with respect to its customers and the macrogrid operator. Issues include rules and costs for connecting to the macrogrid, and microgrid developers' access to reasonably priced backup power, also known as standby service, and to wholesale power markets to sell excess electricity or other services.
- Franchise rights granted to utilities may limit microgrid developers' access to customers. Microgrids may also face challenges in competitive retail access states if they are perceived as locking in customers. Addressing these barriers is essential to the wider deployment of microgrids.
- Linear programming models can help microgrid project developers or energy managers tailor their proposed projects to focus on cost savings, emissions reductions, or independence from the macrogrid; forecast or estimate cash flows and financing needs; and manage power supply and demand. These models could also be useful during a project's development and operational phase.
- To develop supportive frameworks and policies, it will be vital to promote greater dialogue among the finance community, service providers and implementers, government officials at all levels, regulatory agencies, and other stakeholders.

BACKGROUND

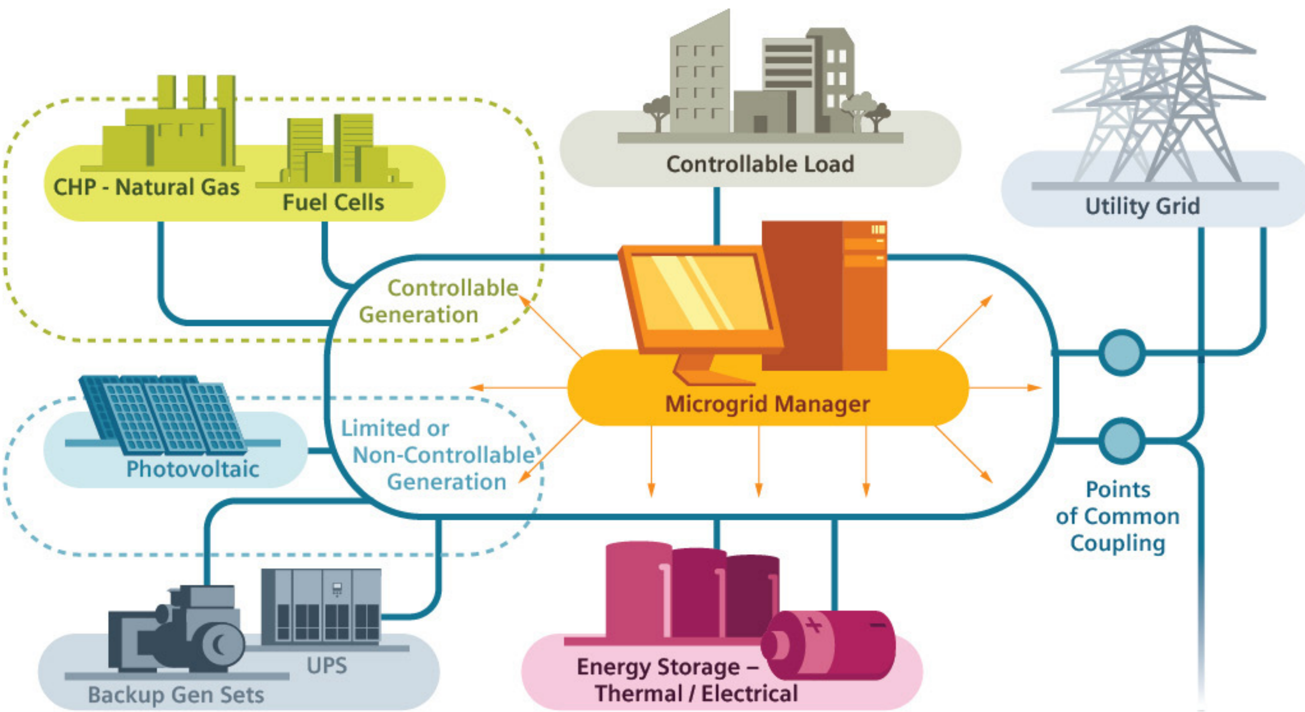
Over the past 10 years, annual carbon dioxide emissions from the U.S. electric power sector have declined nearly 21 percent—by about 500 million metric tons.[1] Electricity-related emissions have been declining due to several factors, including growth in renewable energy, level electricity demand, and a shift from coal to natural gas.[2]

Building on this progress is key to achieving U.S. climate targets and deeper emissions reductions, which scientists say are necessary by mid-century to avoid the worst impacts of climate change.

To that end, private and public entities, including utilities, are exploring distributed generation systems, including microgrids, which can help integrate distributed renewable resources into the grid. Microgrids can also help improve overall electric system efficiency by managing generation and load on a micro-scale to minimize demand during peak periods and influence system reliability standards. However, microgrids are not traditional or typical infrastructure investments for a public- or investor-owned utility, and the existing regulatory system is not structured to facilitate microgrid development by non-utilities.

This paper will discuss financial and legal challenges for microgrids, methods to mitigate project risk, and the types of financing that have been and are becoming available. Then, the paper introduces a new modeling tool that simulates the application of microgrid electricity generating technologies to real-world load characteristics, and presents results from selected use cases that alternatively minimize cost and greenhouse gases, setting forth some observations and insights from the results. Finally, the paper discusses how an enhanced version of the model could reduce financial uncertainty, and be used to determine the trade-offs among the three objectives (i.e., cost, independence from the grid, and emissions), including to optimize operations. Technical issues, including moving away from proprietary technological offerings, as well as developing open standards and options for interoperability, are beyond the scope of this paper, although also relevant to full deployment of this technology.

FIGURE 1: A Sample Microgrid



Elements of the microgrid include: controllable generation like natural gas-fueled combined heat and power (CHP) and fuel cells; limited or non-controllable generation like a photovoltaic array or wind turbine (not shown); backup generators, uninterruptible power supply (UPS), and energy storage capability. Loads can vary significantly. The microgrid manager (at the center of the diagram) balances generation and load. The microgrid interacts with the macrogrid through the points of common coupling. Note that microgrids can also be made up of multiple adjacent interconnected microgrids or a combination of interconnected nanogrids and microgrids.

Source: Siemens, "Microgrid Solutions" 2016. Available at: https://w3.usa.siemens.com/smartgrid/us/en/microgrid/pages/microgrids.aspx

DEFINING A MICROGRID

In 2016, the United States had about 1.6 gigawatts (GW) of installed microgrid capacity out of 1,066 GW total capacity.[3,4] Installed microgrid capacity is expected to increase to 4.3 GW by 2020.[5] Of the 160 microgrids in the United States, most are concentrated in seven states: Alaska, California, Georgia, Maryland, New York, Oklahoma, and Texas.[6] Microgrids mostly use combined heat and power (CHP) and reciprocating engine generators, which use fossil fuels.[7] Microgrids are expected to become greener as future projects incorporate more solar power and energy storage.[8]

Several variations (and combinations) of microgrids are possible:

- **Number of customers:** Microgrids can serve a single building (aka nanogrids), multiple customers in a limited geographic area, or customers across an entire community. Existing microgrids range in size from 100 kilowatts (kW) to a few megawatts (MW).
- **Load types and functions:** Microgrids can either serve load for ordinary commercial reasons (referenced here as a "general purpose microgrid") or serve a community-oriented function. A general purpose microgrid would provide electric power (and may also provide thermal energy) for interconnected customers to displace or supplement the services customers might otherwise receive from the macrogrid. "Community microgrid" is a term often used to describe a microgrid that is specifically intended to serve a public purpose, such as aiding a community during an emergency. For example, a community microgrid might serve critical infrastructure such as police and fire stations, street lights, traffic lights, pumping city wa-

ter and wastewater, and cell towers, to assure they can operate during blackouts of the macrogrid. Community microgrids can also serve general purpose needs by providing power to displace or supplement service from the macrogrid on a day-to-day basis, assuming they are always active, not just during emergencies. Both types can also aid in recovery and re-energization of the macrogrid after a blackout, which is why they are often deemed to provide resilience to the grid.

- **Off-grid loads:** Microgrids can serve power islands, such as remote sites and other load that for whatever reason is not, or cannot be, connected to a macrogrid. In such a case, the amount of generation capacity available to the microgrid must be sufficient to meet the load of all the connected customers, with appropriate reserves. Of course, if a microgrid can connect to a macrogrid, it has greater flexibility, since the macrogrid functions as an additional resource.
- **Ownership structures:** Ownership models include wholly utility-owned, privately-owned, publicly-owned, or some combination of the three. Ownership may, by law, dictate the number and type of customers that the microgrid can serve and, as discussed below, affect the type of financing available. For example, a privately owned microgrid may be limited by franchise laws with respect to serving any load other than its own or loads on a limited number of adjacent properties.

BENEFITS

Microgrids have several benefits to the environment, and to utility operators and customers. They can reduce greenhouse gas emissions in two ways: (1) by offering the opportunity to deploy more zero-emission electricity sources (within the microgrid) and (2) by making use of on site energy that would otherwise be lost through transmission lines and heat that would otherwise be lost up the smokestack. In addition, microgrids can enhance grid resilience to more extreme weather. They also can improve local management of power supply and demand, which have upstream benefits for the whole electricity system.

Microgrids offer the opportunity to deploy greater quantities of variable zero-emission electricity sources. The microgrid manager (e.g. local energy management system) can balance generation from non-controllable renewable power sources (e.g., solar) with distributed, controllable generation (e.g., natural gas-fueled combustion turbines or emerging generation sources such as fuel cells or even small modular nuclear reactors). They can also use energy storage and the batteries in electric vehicles to balance production and usage within the microgrid. When connected to the local distribution network or transmission system, microgrids can also transact from a single node to export excess electricity or import imbalances from the surrounding system.

Power sector emissions could be reduced by using microgrids to reduce the total amount of electricity required. When power has to travel long distances (e.g. from a centralized power station), line losses occur, requiring additional generation to ensure that far away demand is met. Since microgrid electricity is generated adjacent to where it will be used, line losses are minimized and less power is required to meet an equivalent level of demand. Additionally, when electricity is generated from certain centralized power sources (e.g., fossil fuels and nuclear power) a great deal of heat energy is created, and typically released—unused—into the atmosphere. When power is generated close to the end users, it becomes economically feasible to use this heat energy productively, such as heating water or space in nearby homes and businesses. Thus, less fuel is combusted overall, resulting in lower greenhouse gas emissions. Furthermore, carbon dioxide reductions are often accompanied by reductions in other important pollutants like nitrogen oxides, sulfur oxides and even mercury.

As an important component for building greater grid resilience (e.g., from weather-related or cyberattack events), microgrids can continuously power individual buildings, neighborhoods or entire cities. This can include a wide range of demand sources (e.g., residential units, commercial and light industrial facilities), even if the surrounding macrogrid suffers an outage. This concept of a microgrid functioning independently from the surrounding system is known as islanding. Moreover, microgrids are appealing to independent-minded entities (e.g. cities, businesses and individuals) that want to control their own power generation and disconnect from utilities.

By improving local management of power supply and demand, microgrids can help defer costly investments by utilities in new power generation. When sited strategically within the electricity system, microgrids help reduce or manage electricity demand and alleviate grid congestion, thereby lowering electricity prices. This, in turn, could reduce peak power requirements. In this manner, microgrids may support system reliability, improve system efficiency, and help delay or avoid investment in new electric capacity (e.g. "peaker" plants, substations, transmission lines, energy storage or other infrastructure). They can also help the macrogrid recover from a system outage, either indirectly, by sustaining services needed by restoration crews, or directly, by helping to re-energize the macrogrid. For example, New York City's utility is seeking to delay building a $1.2 billion substation in Brooklyn or Queens through a demand management program, which includes a planned microgrid project at a low-income housing community.[9,10] Moreover, in Borrego Springs, Calif., a mixed-ownership microgrid is providing clean, reliable, and resilient power cost effectively to a hard-to-serve, isolated community.[11]

FINANCING

Microgrids are not widely understood, and because each project combines a unique set of factors, financing can be a challenge. Complexity and unfamiliarity with a technology can increase the perceived and actual risks and the resulting cost of capital. Part of the challenge for an investor is that microgrids tend to integrate multiple energy technologies and unique circumstances into a single project. Each project can comprise different electric generation types and sizes, serve a unique load, be situated in a unique geography and market, and be subject to unique weather variability and regulations. These characteristics can make evaluating the project complicated, as each element has its own technological risks, and the ability of the whole to function may be unfamiliar due to limited available experiential data. It has been said, "If you've seen one microgrid… you've seen one microgrid."[12]

Moreover, laws applicable to the provision of electricity retail service vary by state, and some pertinent restrictions may even differ within the state (as discussed below). Both legal restrictions and legal uncertainty may impose additional costs and may have a direct impact on financing. In addition, while tax credits and preferential tax treatment exist for some of these technologies, they differ by technology, region, and ability of a developer to access. For example, solar and fuel cell technologies are eligible for a federal investment tax credit, but a municipality that does not have a federal tax obligation might not be able to use that credit. With so many variables, each microgrid project may require its own customized financial solution, adding yet more costs to the financing process.

Utility-owned microgrids can often be funded by including the capital cost in the utility's rate-base, provided the utility can demonstrate the need for and cost-effectiveness of the microgrid to its regulators.[13] These microgrids simply offer a different technological approach to delivery of traditional services by established service providers. Off-grid, or utility-connected but privately owned microgrids and nanogrids, however, can be much more challenging. They may compete with electric service delivered through existing infrastructure, and face legal and administrative challenges that limit their deployment. Community-owned grids also face financing challenges even in states that have encouraged such projects.[14] So far, much of the funding that communities or other developers have tapped for microgrids comes from government sources (state and federal) and have included bonds, tax credits, grants, loans, tax deductions, and credit enhancements.

For privately owned microgrids, an option may be project financing—a structure in which debt is acquired and repaid based on the cash generated by the project, without recourse to the equity holders. In this type of structure, there is emphasis (in addition to the factors above) on the quality and quantity of the revenue that the project will generate. Who will purchase the generation and services provided by the project? The purchasers (commonly referred to as "off-takers") are a critical factor, because the creditworthiness of the project will be affected by the creditworthiness of the off-takers. Investors will also look at the projected operating costs, and the stability and certainty of those projections. Further, the terms and conditions under which the off-takers will purchase the microgrid's output and services matter, since together with the operating costs, these factors go to the expected stability of the microgrid's revenue streams.

Microgrids generate revenue in several ways. Providing metered electricity to consumers within the microgrid network provides a steady stream of income to a microgrid owner. Investors will consider the basis on which these sales are made, including the duration of their commitment and the conditions under which the off-takers' payment obligations are suspended or relieved, as well as the creditworthiness of the off-takers. Providing metered thermal energy, such as hot water, steam or chilled water—an offering that most electric utilities do not provide—can be an additional source of revenue for the microgrid owner. Owners can capitalize on other attributes of the microgrid. A highly reliable and resilient microgrid may attract a premium tariff from commercial entities that require a higher level of service and have a low tolerance for disruptions. For example, a grocery store may be willing to pay a higher electricity price in exchange for a guaranteed uninterruptible power supply to help it keep valuable refrigerated and frozen food from perishing in the event of a grid outage. A data center or other service provider that cannot afford to be offline even for an instant might be willing to sign a contract for a premium service. Additionally, consumers with large heat-generating loads, such as grocery stores and data centers provide opportunities for further collaboration between thermal and electric microgrids, which can augment revenue streams and carbon benefits. The waste heat generated from refrigeration and freezers from food storage can be a thermal energy source to low-temperature thermal grids. Similarly, heat from data centers can be integrated into thermal grids. If the microgrid includes renewable generation, it may be eligible to generate renewable energy credits (RECs). While some owners will retire these RECs to assure their claim to "green" power, others may sell them, creating yet another revenue stream. Finally, excess power can be sold back to the larger grid, or the microgrid could generate revenue by providing other macrogrid services, such as participating in demand response markets or by providing frequency regulation services.[15]

This revenue will be offset by operating costs, including fuel, labor, and administrative costs, as any utility service provider will incur. Participation in markets to sell demand response, frequency regulation, or other services has a cost, as the microgrid owner will need to become a market participant or contract with a marketer able to make the transactions. In addition, the microgrid owner may need to purchase power from the macrogrid owner or the wholesale market, both for its own needs or its customers' needs, in excess of that which it provides (unless the customers purchase their excess needs directly). Like any business, meeting such obligations means the microgrid will have working capital requirements, which also need to be considered when arranging its financing.

Due to a general lack of standardization and perceived high risk, some financiers may be discouraged from investing in microgrid projects outright. Others may be ready to invest, but will establish financing terms that could be a heavy burden for private developers. Moreover, developers of microgrids have a higher hurdle to clear to convince investors of the viability of individual projects, i.e., relative to a more straightforward solar or wind farm. The uniqueness of each microgrid makes investors' due diligence more difficult and increases transactional costs associated with financing. Another challenge is potentially long payback periods for projects, which require sustained long-term operations and can increase project risk.

These many challenges are being addressed in a variety of ways. Newer control and communication technologies are making microgrids more feasible, cost-effective, and valuable, enhancing their performance and spurring their development. Microgrid developers that can replicate successful project models may be able to develop a relationship with investors that reduces their transaction costs, as the investors become more comfortable with the developer's model. Financial feasibility studies, modeling, state funding, and public-private partnerships all could play a growing role in overcoming financial hurdles.

One way to quantify and reduce microgrid development risk is by performing a financial feasibility study (a standard industry practice), which identifies the strengths and vulnerabilities of a project. The key components of the financial feasibility study are calculating the project's start-up costs, identifying the sources of funding, and calculating the project's likely returns. Buying electric generation equipment typically accounts for the largest share of the development and construction cost.[16] Each project's starting point is likely to be unique; existing electrical infrastructure or generation assets can help mitigate the cost of constructing the system. Other costs to consider are infrastructure build-out and microgrid control systems. Development and construction costs can escalate depending on the location of the microgrid, its degree of sophistication, and whether the project is designed to be scalable.[17]

Simulation models, like the one discussed in this paper, could be fine-tuned to provide probabilistic profiles of project cash flows and returns, mitigating some of the uncertainty around the economics of microgrids. Key model inputs include microgrid generation and load profiles, linked energy market data (e.g. historical market prices and prices for grid services), and regulatory environment constraints.[18] By providing grant funding for feasibility studies, states can help promote microgrid development.

For a potential developer seeking financing, state funding would be a first option to explore. In 2014, Massachusetts gave $18.4 million to cities and towns for energy resilience projects, including microgrids.[19] Through a request-for-proposals (RFP) process, Connecticut has allotted $20 million to microgrid projects, with most of the funding going to municipal projects.[20] California funded $27.3 million for 10 microgrid and electric vehicle charging projects.[21] New York has established a $40 million grant program (i.e., NY Prize) to create community microgrid projects that can serve as business model templates for other communities.[22] New Jersey is also looking to spur community microgrids by offering funding for feasibility studies.[23] Additionally, New Jersey created a $200 million resilience bank for the development of distributed energy resources.[24] Other states including California, Connecticut, and New York, have developed clean energy banks (CEBs or green banks), which leverage both public and private dollars to fund clean energy, including some types of microgrids.[25]

Another strategy for financing microgrids that appears to be gaining popularity is the use of public-private partnerships.[26] These long-term collaborations between the private sector and the government allow for flexible sharing of project risks and management.[27] Importantly, projects are able to be made viable or "bankable," i.e., structured such that cash flow is capable of meeting its debt and equity investor return requirements.[28] Mixed ownership microgrid projects, which could include money from public institutions, utilities, and private entities, have increased from nearly zero in 2013, to a projected 38 percent of the market in 2016.[29] Recent examples include cities and counties partnering with utilities and private businesses to develop microgrids at Peña Station Next in Denver and two government facility microgrids in Montgomery County, Maryland.[30]

CEBs are governmental or quasi-governmental organizations designed to maximize the use of limited public funding to advance deployment of clean energy technologies.[31] It is reasonable to assume that CEBs and microgrid developers' interests would be aligned and that CEBs have the tools and expertise to help increase the number of project deployments. Additional sources of finance from a wide range of public and private sources are summarized below.

LEGAL FRAMEWORK

Any investor in a microgrid project will be concerned with the legal environment in which the project will operate. Legal hurdles can be costly, can limit the ability of the project to operate optimally, or can even prevent its operation.

Microgrids face three types of legal hurdles: (1) law that prohibits or limits specific activities; (2) law that increases the cost of doing business; and (3) uncertainty, including the risk that new law will be implemented to regulate microgrids and impose restrictions or costs not anticipated at the time of development or construction. Conversely, law can grant rights and clearly delineate obligations, facilitating development and financing, and making the project more attractive to potential customers.

Law can include statutes, regulations, market rules, local ordinances, tariffed rates, terms and conditions (including interconnection rules and fees and stand-by power charges), or even electrical codes. Risk related to future changes in law is unavoidable, and exists in

TABLE 1: Sources of Microgrid Finance

PUBLIC FINANCE (FEDERAL, STATE AND MUNICIPAL)	DESCRIPTION
Tax-exempt bonds	Can be issued if the microgrid is public or a public-private partnership with a city, state, or other municipality
Tax credits	May be applicable when certain eligible renewable generation sources are deployed as components (assuming taxable entity is involved in project to realize benefit)
Grants	Funding that does not have to be paid back
Loans	Public financing that must be paid back
Tax deductions	Specific federal or state deductions incentivizing projects (assuming taxable entity is involved in project to realize benefit)
Credit enhancements	A way in which a company attempts to improve its credit worthiness (e.g. supplying additional collateral, insurance or a third-party guarantee) to the lender[32]
Clean energy banks	Quasi-governmental organizations that assist clean energy projects like microgrids
Commercial property assessed clean energy (PACE)	Public-private program for properties to obtain low-cost, long-term clean energy financing available in 16 states[33]
Resilience bonds	Could help lower project costs, if the microgrid project meets certain criteria
Power purchase agreements (PPAs)	Project income from a public entity for services provided over a fixed term
PRIVATE FINANCE	
Equity financing	Earn investors an unspecified return
Debt financing, loans	Line of credit from private banks, institutions
Corporate bonds	Long-term, large-scale financing
Energy savings performance contracts (ESPCs)—Energy service companies (ESCOs)	Companies that help develop energy projects with a focus on energy savings, from which they earn their service fee[34]
Power purchase agreements (PPAs)	Project income from a private entity for services provided over a fixed term
Third party model	A financing arrangement in which a third-party entity owns the system and a customer leases or contracts with the provider for services

all aspects of business. But where the framework for an emerging technology is completely lacking, the risk is heightened due to the expectation that the void will be filled soon, although the contours of the new law are unknown.

Microgrids (nanogrids) confined to a single site and a single owner, such as within an industrial complex or a building, are generally the easiest type of project to assess. No state prohibits an entity from self-supplying its electrical needs, although the law may or may not be hospitable to such arrangements and may limit the use of leasing arrangements or other third-party services.

Microgrids that serve multiple customers, however, face the uncertainty of a void in the law. Connecticut was the first state to develop a legal definition of a microgrid, which it did as part of a larger effort to promote community microgrids for resilience in the wake of Hurricane Sandy.[35] The state even integrated into its definition of "Distributed Energy Resource" the possibility that such distributed resources might interconnect with a microgrid.[36] However, the Connecticut law is narrowly tailored to promote the development of microgrids "to support local distributed energy generation for critical facilities," such as hospitals and water treatment plants.[37] Thus, while Connecticut's program is a significant step forward, it is not designed to provide a complete framework for the development, connection, and integration of microgrids, including those that serve other purposes. The proposed owner of a private-sector microgrid would still face multiple hurdles. Other states are even further behind in providing legal certainty.

Some of the specific issues common to any type of microgrid:

- **Interconnection:**

  Even if a single owner/operator controls the microgrid and the associated load, the owner/operator must assess the cost and requirements for interconnection to the wider grid. At the distribution level, the terms and conditions for interconnection, as well as the costs, will vary by state and generally also by utility, and may not be well-developed, particularly as applied to microgrids. These rules are often subject to state utility commission oversight.[38] A project that connects directly to the transmission system will generally interconnect under rules and regulations that have been established by the Federal Energy Regulatory Commission (FERC), but those standard terms and conditions are written for generators (small or large) and have not been specifically adapted (yet) to cover the full range of potential microgrid operations.[39]

- **Back-up, maintenance, supplemental, and interruptible service rates:**

  The developer of the microgrid will also need to assess the terms, conditions, and rates for back-up, maintenance, and supplemental electric service (also known as "standby" service). These types of electric supply service are required to meet customer needs beyond that which the microgrid can supply, including during periods in which the microgrid or some portion of it is taken out of service for maintenance.

  In the past, some franchised utilities[40] provided such services at non-competitive rates that discouraged self-generation. To remove that barrier, a 1978 federal law, the Public Utility Regulatory Policies Act (PURPA), mandated that electric utilities sell back-up, maintenance, supplemental, and interruptible electric service at non-discriminatory rates to any generator (and its associated load) [41] that met certain federal standards.[42] However, not all microgrids will meet the standards necessary to come within the protection of PURPA, and even for those that do, the standards are implemented differently from state to state. Further, the federal mandate bars discrimination, but does not prohibit the assessment of charges that are based on consistently applied costing principles, and even appropriately developed charges may be onerous.

  As more customers find alternatives to utility-supplied generation, some utilities have sought to impose special charges on customers who they deem to be not paying for their fair share of fixed costs for the system. To date, these efforts have been directed primarily toward customers who have installed rooftop solar,[43] but the same underlying concerns of supporting the costs of a grid that is used more intermittently apply to microgrid customers, too. How these concerns will be resolved remains to be seen. At present, there is little consistency from state to state, or even from utility to utility regarding these charges, and there may be increasing pressure to introduce new rate structures as more generators are added to the distribution system. Thus, the cost of back-up, maintenance, supplemental, and interruptible electric service is an important area for inquiry and, due to the present state of flux, may be deemed a potential risk in any financing deal.

- **Operational uncertainties and jurisdictional complexities:**

  A microgrid may seek to provide power or other operational services to the grid for compensation.[44] If such a revenue stream is available, it may be a positive factor in financing, depending on the degree to which it is predictable and secure. However, participation in wholesale markets may bring complicating factors as well, as the issues related to allowing a microgrid to participate in the wholesale market are not yet fully understood and may raise jurisdictional conflicts. For example, in testimony before FERC in May 2016, Chantal Hendrzak, executive director of market evolution for PJM (the regional transmission operator for the mid-Atlantic states, stretching into the

Midwest), stressed the importance to PJM of being able to "see" the load served by the microgrid and have greater dispatch control.[45] These issues could be resolved by requiring certain controls and communications equipment, although mandating new standards is particularly complicated when the state-jurisdictional distribution-level resource such as a microgrid is participating in a FERC-regulated wholesale market.[46] Indeed, Ms. Hendrzak noted, with respect to microgrids:

> "We do not believe that this area is ripe for a NERC standard at this point.[47] Moreover, given jurisdictional issues, such a standard may only complicate matters. Rather, continued work and encouragement by this Commission and state Commissions on developing a harmonious tariff that bridges federal and state jurisdiction is a goal worth working toward in the near future."[48]

While there are clearly mutual benefits to integrating microgrids into the markets, these comments underscore the uncertainty regarding how to best do so. As the market rules and engineering and reliability specifications evolve, there may be substantial costs as well as benefits, which will need to be considered in the economics of future projects.

A microgrid that seeks to serve multiple entities may face additional challenges:

- **Franchise rights:** Although 17 states and the District of Columbia permit competitive retail access, the other states have not adopted retail access, which may curtail the rights of one person to provide electricity to another. For example, Iowa statutes grant the Iowa Utilities Board the authority to grant exclusive franchises.[49] This type of law could limit a privately owned microgrid from serving loads other than those of the microgrid owner. But the Iowa law does permit a power provider to serve a small number of customers, incidental to the generation of its own power.[50] Thus, certain microgrids could fit within the existing law, but it's a narrow path.
- **Limits on competitive access:** In states that have competitive access, customers can choose their service provider, which presumably could include a microgrid. But where a microgrid project encompasses a geographic area (e.g., a city block), regulators may be concerned that authorization of a microgrid will have the effect of granting a franchise, by limiting the ability of the interconnected customers to change suppliers, and thereby take away the right to competitive access. This problem was raised by the Maryland Public Service Commission in a recent decision (see box), although in context, the concern may have been heightened because the proposal was from the incumbent utility and it was not clear that the customers connected to the microgrid would self-select, with an option to opt-out.[51] But the fact that the customers would be served exclusively by the microgrid when islanded is the essence of a microgrid. Lawmakers and regulators will need to determine if there are any consumer welfare concerns related to microgrid service (including exclusivity during islanding), and determine how to address those concerns as part of any future policy.
- **Regulation:** Even if the proposed microgrid owner is not restricted from serving others, state laws governing distribution service providers may draw no distinction between a provider serving the general public and one seeking to serve a small defined area. Thus, the microgrid owner risks undertaking the same regulatory obligations of a macrogrid owner, which may be costly or impose regulatory burdens, such as requiring approval to issue stock or change ownership.
- **Rights-of-way:** State laws often grant distribution providers some rights to cross public streets and to exercise rights of eminent domain. A microgrid provider that seeks to serve only a small defined population may not have similar defined rights, or the ability to acquire those rights may be coupled with undertaking other responsibilities of a "public utility" (which could be burdensome).
- **Cost allocation:** If a microgrid purports to provide a benefit to the community, should non-connected customers who may benefit bear a portion of the costs (e.g., in their distribution charges)? Or should the macrogrid operator seek regulatory authorization to pay the microgrid owner for services on an as-procured basis, and then recover those costs from its ratepayers? A regulatory commission should give careful consideration to this question, because if microgrids can deliver potential public benefits, then rates should be fine-tuned to encourage their development.

BOX 1: Proposed Maryland Public Purpose Microgrids Raise Questions

A microgrid that will serve unrelated parties faces complex issues surrounding who will participate and how the cost of the microgrid will be recovered (which is essential to financing). A recent Maryland Public Service Commission decision rejecting a proposal from Baltimore Gas and Electric Company (BGE) for a public purpose microgrid illustrates the questions.

Maryland's electric industry was restructured in 1999 and BGE, an incumbent utility, became primarily a provider of transmission and distribution services. Although Maryland has competitive retail access and competitive generation, in 2006, the Maryland commission was granted authority to approve construction and cost recovery for new generation resources by an incumbent investor-owned utility "to meet long-term anticipated demand in the State."[52] Under that authority, BGE proposed two public purpose microgrids, one of 2 MW and one of 3 MW, that would be capable of islanding during a grid outage and would support critical facilities including "merchant services" such as groceries, fuel, restaurants, and banks" that would aid the community during the outage and facilitate recovery.[53] It proposed to recover the $16.2 million in expected costs through a rate surcharge applied across all customers.[54]

The commission raised numerous concerns as grounds for its rejection. In addition to questioning whether a surcharge was the appropriate vehicle for cost recovery (which is largely a state-specific issue), the commission questioned the justifications offered by the utility for cost recovery and how it allocated costs to beneficiaries. It found BGE failed to adequately quantify the "tangible benefits" of the microgrids "including any benefit for avoided customer interruption at each microgrid location."[55] It sought evidence that customers not connected to the microgrid would be able to travel to the microgrid locations during emergencies to avail themselves of the services supported by the microgrid and that the merchants supported by the microgrid would be able to provide emergency services, given that they might not be prepared for large numbers of customers or able to secure the supplies needed in an emergency.[56] The commission also suggested that the commercial enterprises providing these emergency services would receive a financial gain from doing so, and therefore should have been asked to take direct responsibility for a portion of the costs.[57] It also faulted BGE for not finding "alternative funding through state or federal agencies or the local subdivisions," although BGE stated it was unaware of any available at the time.[58] It also challenged BGE's explanation that it selected these proposed sites based on reliability data showing the grid could use additional support at these location, stating that BGE had not shown that its proposed sites were selected with community input or coordinated with state and local emergency planning, and noting commission staff's concern that BGE had not shown that its data was still valid given other recent reliability grid projects.[59] The commission further raised concerns that the proposed projects did not include renewable generation, and might not provide the desired reliability because of their lack of fuel diversity.[60]

The decision highlights Maryland's need for a clear microgrid policy. Collaborative development of a framework defining regulators' goals and expectations, cost allocation and rate recovery principles, and a multi-agency process to integrate microgrids into emergency planning would facilitate future proposals' success.

The Maryland decision summarized in the box illustrates that microgrid providers may face substantial challenges in seeking cost recovery through rates. But it also raises more general concerns that might be applicable when seeking either rate-payer funding or private investment. In the effort to persuade lawmakers and policymakers to accommodate or encourage microgrid development, it will be important to be able to state and quantify the benefits, show how the microgrid will deliver the promised reliability benefits during a crisis, and gain the support of other agencies and organizations with whom the microgrid owner/operator would coordinate in times of crisis. Determining how to allocate the costs across beneficiaries is also a concern, regardless of whether the allocation is done through utility rates or by private contracts.

The Maryland Public Service Commission's competitive concerns are particularly noteworthy because they raise a fundamental issue. As noted above, some states have exclusive franchises, which can limit a microgrid's ability to attract new customers. But Maryland does not have exclusive franchises; it has competitive retail access. On its face, it seems this would make it easier for microgrids to develop. But the commission found that although customers could exercise customer retail choice when the microgrid was connected to the macrogrid, when islanded, the customers "will have little to no access to retail choice in microgrid services."[61] The trade-off of supply security and the ability to easily select suppliers is inherent in a microgrid, and laws should make clear that consumers who wish to make this trade-off may do so. But, as the law stands now, microgrid owners seeking to serve new loads or customers who are inadequately served under their existing arrangements may find more flexibility in the law to acquire customers than microgrids seeking to serve customers presently served by an incumbent utility.[62] If microgrids are to reach their full potential, regulators will need to determine the conditions under which a customer may opt to be served by a microgrid rather than through traditional means, and how that decision will be honored.

While there are these many common areas that need to be addressed, variability in existing law and practices across states, and sometimes within them, add another layer of complexity. Resolving this variability would benefit the market.

In sum, financing would be facilitated with clearer laws.

- The applicable law may need to vary depending on whether a microgrid owner is proposing only to self-supply or serve others, and so it's important to define what type(s) of microgrids are contemplated and which laws apply to which type. For example, if microgrids are authorized to serve unsophisticated users, the commission may need to consider developing consumer protection laws; whereas a privately owned microgrid that serves a single user or a small group of sophisticated users (e.g., large industrial consumers) should be able to establish the rights and obligations of the microgrid and its customers by contract and the regulator's focus should be only on any impact the microgrid has on service to the general public.
- All microgrids need clarity with respect to their rights to interconnect, including the rules and regulations around separating (islanding) and reconnecting.
- Those microgrids that serve customers (other than the owner) need certainty as to their rights to acquire customers, and the customers need certainty as to their rights to join or depart the microgrid (whether defined by a contract or a tariff) in both areas with retail franchises and areas with competitive access.
- Where the microgrid is providing premium services, such as enhanced reliability, it may expect compensation. If a portion of this compensation is expected to come through regulated rates, regulators need to articulate the type of cost-benefit analysis they require to support such a request and other terms and conditions of such service they expect to see before approving rate recovery.
- Microgrids need just, reasonable, and non-discriminatory rates for their purchases from the grid and non-discriminatory access to make sales to the grid. Just as some jurisdictions, such as Minnesota, are now giving greater consideration to the contributions that distributed solar makes to the grid, including for emission reductions,[63] regulators need to give fair weight to the benefits microgrids provide to the system, as well as the costs of service, when considering how to structure rates at which microgrids are served.

Investors relying on the flow of funds from the microgrid project, whether generated from a rate tariff or a PPA, will appreciate the certainty of understanding the microgrid owner's obligations and rights under law, so they can better assess the microgrid owner's ability to meet its obligations and its costs of doing so, as well as the expected benefit stream.

MICROGRID OPTIMIZATION MODEL

Microgrids face financing challenges because of the current legal landscape and because their unique, non-standardized nature creates uncertainty about their economic viability. One way to address these issues and examine the benefit of potential microgrid policies is through mathematical models. Linear programming models have been applied to a broad range of problems across many industries.[64] Generally, these models use an objective function to optimize (i.e., minimize or maximize) cost, revenue, emissions, or other variables of interest, subject to several real-world constraints.

The model introduced here could be applied to select the group of technologies that best meets a project sponsor's objectives, e.g., for emissions reductions, or ability to function in isolation from the grid; to minimize capital investment, operating expenses or both; or to develop operating profiles that meet the project sponsor's preferences with respect to emissions, cost minimization, or independence from the macrogrid.[65]

The model as presently developed minimizes either the microgrid's operational costs or its carbon dioxide (CO_2) emissions over a 24-hour period through linear programming with several constraints on: the load profile, generation resource technology characteristics, and resource availability (e.g., for renewable technologies or macrogrid resources). This could be enhanced to include operational constraints, such as minimum run times based on manufacturer's recommendations, limited availability (e.g., solar intensity during the day, wind limited to a profile appropriate for the geographic location), and technical constraints (e.g., battery charge and discharge profiles). Additionally in the future, the model could consider capital costs of microgrid generation technologies. Model equations, data, and other technical details are available in the Appendix.

The model is configured for a user to design a notional microgrid by selecting from a menu of energy generation resource technology options. The technology options available in this model follow from observations of currently adopted technologies in other microgrids **(Table 2)**. The user can also select whether to run the microgrid in island mode (i.e., independently) or in connection with the larger grid. Furthermore, this model takes into account the adjacent market costs and emissions of the macrogrid, which informs decisions such as when and how much power to take from the macrogrid and when it is most economical to charge or discharge storage devices.

In accordance with the user's selections, the model determines which technologies to employ and at what capacities to best meet the system load to either minimize operational cost or minimize CO_2 emissions. Finally, the model creates a graph that shows which technologies are implemented and at what capacity for each hour of the day to match the anticipated load or customer demand. Additional operational measures, such as implementing demand response to limit or defer peak demands, may also be available to the microgrid operator, although

TABLE 2: Microgrid Technology Choices

TECHNOLOGY	BENEFITS	CHALLENGES
Microturbine	Thermal recovery improves efficiency Thermal output available for residential or small commercial apps Operable as base, peaking, or back-up Commercially available in limited quantities	Insufficient thermal output for industrial applications Efficiencies are much lower than larger central power combined cycle turbines, so emissions are higher.
Diesel generator, internal combustion engine	Power delivered when utility is unavailable Fast startup allows less sensitive processes to be served without need for UPSs (emergency lighting, HVAC, elevators, some manufacturing processes). Very mature, stable technology Can be paralleled to grid or other generators with controls package Can be very efficient when combined with heat recovery	Insurance policy effect: Capital is only being used when back-up generator is running. Marginal cost of production generally favors utility source in all but rare occasions. Environmental issues: emissions and noise Possible on-site fuel storage needs Vulnerable to flooding

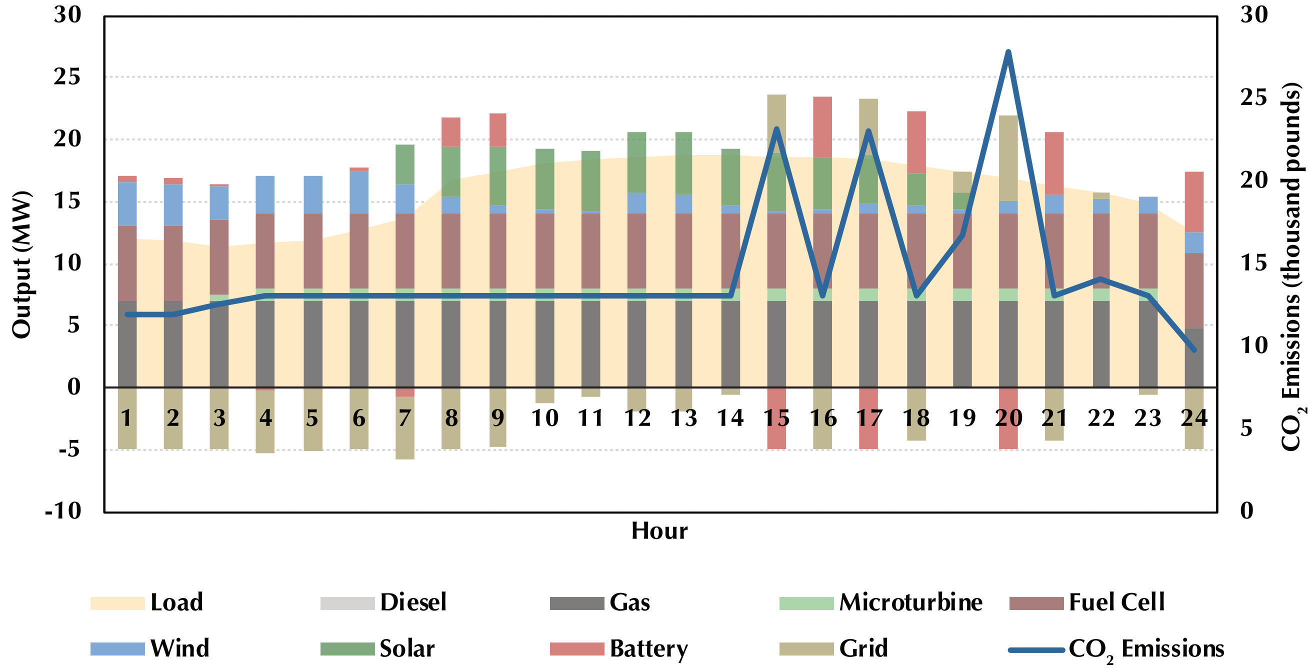
TABLE 2: Microgrid Technology Choices, Continued

TECHNOLOGY	BENEFITS	CHALLENGES
Small gas combustion engine	Highly efficient when used with thermal recovery Technology commercially available today—most likely candidate for on-site needs greater than 3 MW in distributed generation application Can operate baseload, back-up, or peaking Several manufacturers Relatively low installed costs	Potentially onerous siting and permitting requirements Environmental issues: emissions and noise Possible on-site fuel storage needs
Fuel cell	Very high fuel efficiencies from hydrogen to electricity Potential to operate base load with utility back-up Possible residential application—a no-moving-parts energy appliance Very high efficiencies when combined with heat recovery Green technology: Water and heat are only emissions from hydrogen fuel, low emissions from other fuels.	Few commercially available devices Most research efforts are for automotive applications. Need for fuel reformer in almost all applications (reduced fuel to electrical efficiencies) Not a zero-emission technology—the effect of that may vary by state. Cold start is 1–2 days for MCFC, 3 hours for PAFC, 1 hour for PEMFC, and 2 minutes for SOFC[66]
Wind	No variable costs for fuel In utility implementation, zero emissions may allow green power price premium Mature technology Multiple manufacturers	Need to meet siting requirements Generation is intermittent, and energy output can vary with wind speed squared or cubed over operation range. Not appropriate as backup or off-grid applications. Needs utility source for energy purchases and sales Can require footprint up to 100ft²/kW
Solar PV	No variable costs for fuel No moving parts—inexpensive maintenance and long life No emissions, no noise Can be used for peak shaving in summer months (winter peaks are typically before dawn or after sunset in many regions). Highly reliable, mature technology	Large footprint (600 ft²/kW) High installed costs Not suited for baseload, highly intermittent (diurnal and weather impacted) Not suited for back-up except when accompanied by storage Variable energy output

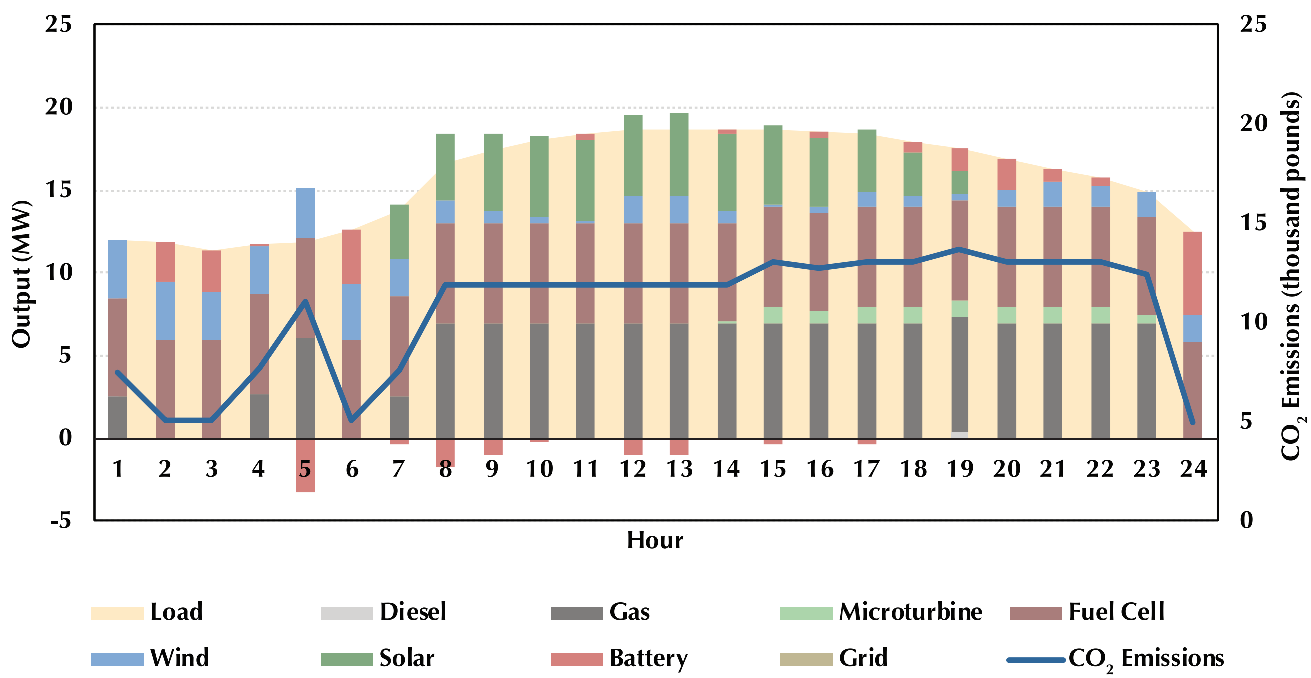
Additional challenges underlying the choice of technologies include available land, adequate rooftop space, connection to natural gas supply, and the limits of theoretical benefits of the technologies. Many fuel cells use natural gas to derive their hydrogen; the notional fuel cell in this model uses natural gas. Power quality is also an issue; many commercial and military microgrids have employed battery storage for frequency control and stable outflow of electric power (e.g. solar PV, wind and diesel gensets have variable power cycling).

Source: Capehart, Barney L., "Distributed Energy Resources." Whole Building Design Guide. October 2014. https://www.wbdg.org/resources/der.php.

FIGURE 2: Microgrid Model Output, Minimize Cost



Microgrid Model Output, Minimize Emissions



The objective function is to (a) minimize cost (top figure) and (b) minimize emissions (bottom figure). Note that negative values for 'Grid' indicate that the microgrid is selling electricity to the macrogrid and negative values for 'Battery' indicate that the microgrid is being used to recharge the battery. Conversely, positive values for 'Grid' indicate that macrogrid purchases are being made to supply the microgrid and positive 'Battery' values indicate that the microgrid is utilizing the battery resource for electricity. Carbon dioxide emissions are the total emissions produced by the microgrid, inclusive of grid purchased electricity when that activity is occurring.

those are not presently built into the model as selectable options.

With this model, a developer or energy manager can test *a priori* many technology combinations to determine the optimal resource portfolio of their intended system design. Model outcomes, illustrate not only the optimal resource commitment schedule, but also provide specific insights into the emission profile of each hour's resource combination. By varying the resource portfolio in subsequent iterations, the developer or manager can assess which portfolio will yield the preferred emissions and cost profile.

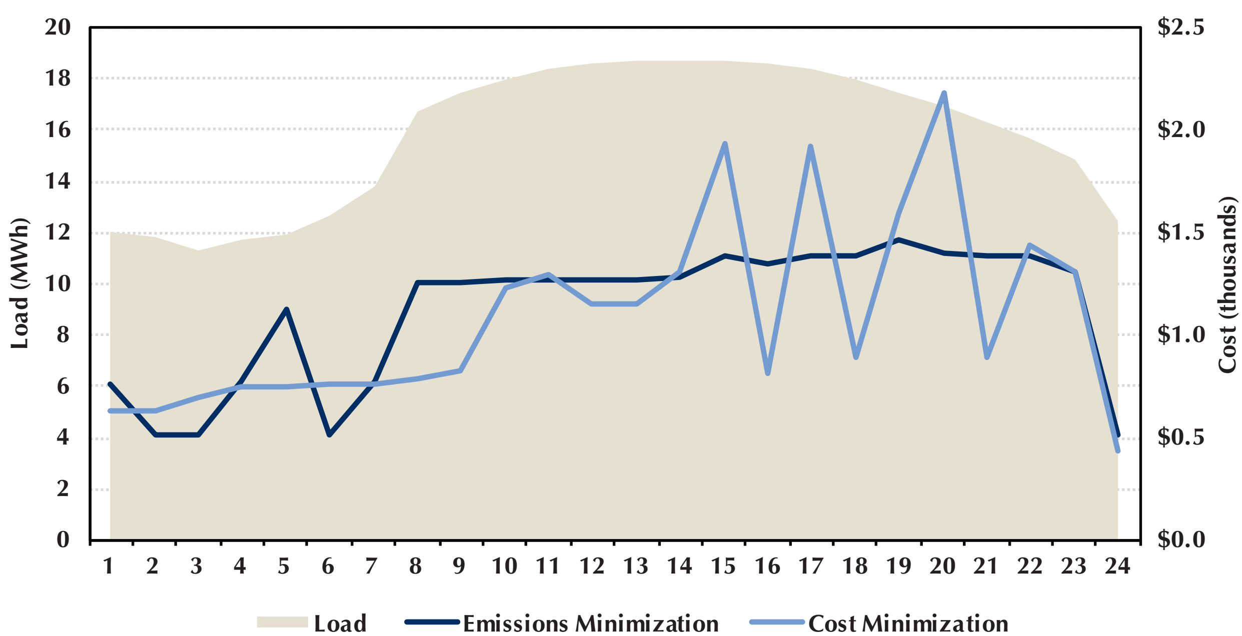
The sample output **(Figure 2)** demonstrates how the model can serve as a conceptualization and learning tool for a project developer or an energy manager by helping to assess the viability of different technology combinations in a microgrid. For the purpose of demonstration, the actual load profile for one year for The George Washington University campus was imported and is used in the examples.

For purposes of demonstration, all resource technologies were selected, that is, made available to the microgrid (and as discussed below, the availability profile for the intermittent resources is set at maximum output for all available hours, although these profiles would need to be adjusted based on geographic location, and would change significantly as a result). The top panel of **Figure 2** depicts a model scenario with cost minimization as the goal, and the bottom panel shows the results of an emissions minimization scenario. Consistent with the objective function, the emissions minimization scenario leads to lower emissions than the cost minimization. In fact, the emissions scenario meets the local demand without grid purchases. Whereas the cost minimization scenario relies on consumption from the grid, which is less expensive at times, but has a higher emissions intensity than the technologies in the microgrid at the location being studied.[67]

Additional observations from the two optimizations include:

- Diesel generation is an option in the emissions minimization scenario; however, its high emissions profile limits its use, and natural gas generation becomes a more optimal resource to compensate for the variability of wind and solar. In this case, the total system operation cost is \$26,787/day; and the total CO_2 emissions is about 255,000 lbs.

FIGURE 3: Cost of Supply Under Cost and Emission Minimization



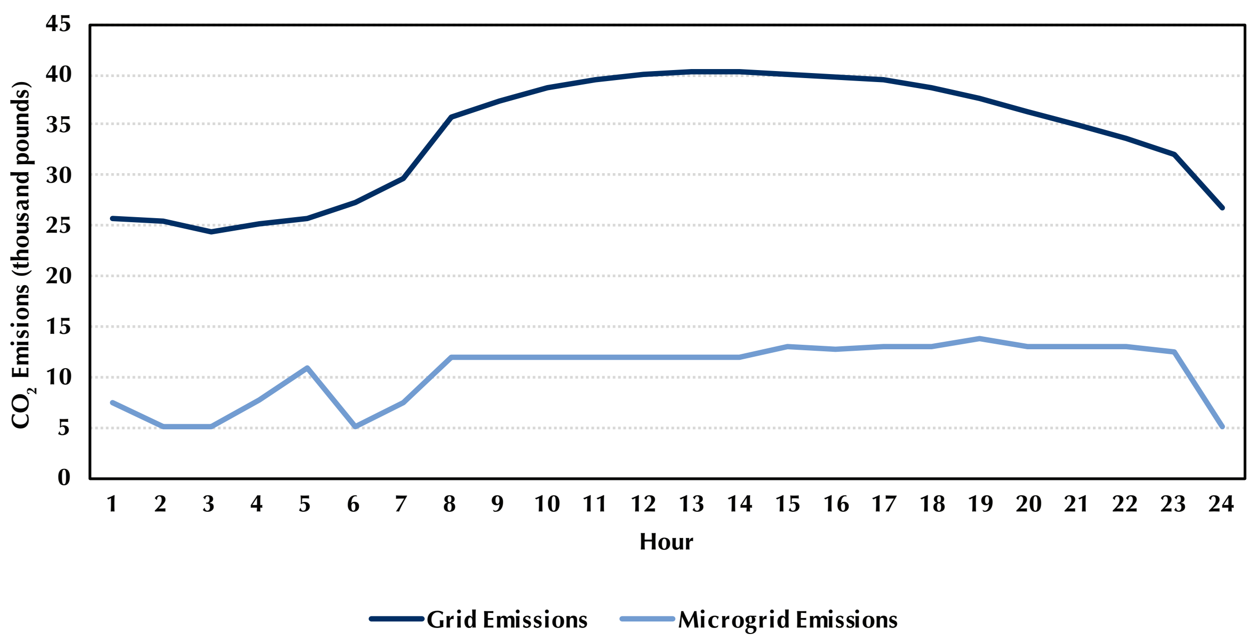
- Under cost minimization scenarios, natural gas, fuel cell, and microturbine are the dominant technologies. The battery system is often utilized, while the benefit of grid trading is persistent the entire day. In this case, the total system operation cost is $26,116/day; and the total CO_2 emission is about 350,000 lbs.

The modeling tool can also be used to evaluate how the cost profiles change when the goal of the microgrid changes from cost minimization to emissions minimization. In **Figure 3**, the cost profiles under the two regimes are superimposed on the average load profile for the GW campus. The microgrid making greater use of the emission-free technologies provides the desired environmental benefit, but those benefits come at the expense of higher total costs. Note that the cost profile under the cost minimization scenario is highly variable as the system experiences low and high costs following episodes of battery discharging and charging, respectively. This is most evident during hours 15–20 and it highlights the value of battery storage in a microgrid.

Figure 4 compares the emission profiles of the stand-alone microgrid with that of the macrogrid for supplying the same daily load profile. Operationally, the microgrid emits less CO_2 than the grid on a ratio of one to three on average. Grid-only emissions typically follow the daily load profile while the microgrid emissions path underlines the benefits of storage and the renewable resources. Additionally, microgrids can improve performance by implementing demand response and by optimizing storage, which can offer cost advantages and mitigate the technological imbalances of intermittent resources, especially when these factors are considered at the design stage of the system. The charging or storage of energy (e.g. batteries) during hours of limited demand and their discharge at peak time demonstrates the value of off-peak generation from renewable technologies. However, the downside is demonstrated in the volatility of the cost (**Figure 3**). Also, selling into the grid offers a tremendous cost reduction opportunity over certain hours of the day when the sale to the grid is considered optimal (**Figure 2**).

Greater use of fossil fuel technologies increases CO_2 emissions and provides a level of operational certainty, but modeling allows for better quantification and evaluation. Fuel costs increase microgrid operating costs directly, depending on the duration of deployment of the underlying technology. However, the amount of CO_2 emissions is modulated by the presence of zero-emission technologies in the mix. For example, diesel

FIGURE 4: Emission Profiles of Stand-alone Microgrid Versus Grid-only Consumption



technology offers the most expensive and highest CO_2 per kWh, thus the diesel technology is seldom chosen in either the cost minimization scenario and less so in the emissions minimization objective. Combining these two observations implies that the optimal commitment pattern seeks to maximize the employment of technologies that have no fuel costs such as solar and wind but require that there is sufficient backup in a technology such as natural gas-fired generation and/or battery storage.

Additional development of the model would yield more useful results. As shown in several scenarios, the fuel cell is a perfectly viable technology option given its persistent choice by the model. However, in the real world, fuel cells have not been as reliable. Observed fuel cell outages, not captured in the model but noted from operational literature, results in increased utility purchases, significantly higher peak power demand charges, and losses of heat supply, which need to be replaced by natural gas purchases. Over time, these random outages could reduce the cost-limiting and emissions-reducing benefits of this technology. Some of the challenges faced by each of the microgrid technologies are listed in **Table 2**.

With additional analysis, the model may be improved to better reflect a more approximate match of resource availability in any given geographic location. For example, the current model has taken the availability of solar intensity to be maximum for the hours for which solar irradiance is assumed available, rather than reflecting its variability over the course of the day or throughout the year. Additionally, the availability of wind intensity over the course of the day was also assumed to be its maximum output at all times. However, incorporating more realistic availability profiles of these technologies (and the load they serve) will lead to a stochastic optimization model, adding additional complexity and potentially creating issues for the solver environment in Microsoft Excel (which presently solves a somewhat simplified model successfully).

In addition, the capacity of the chosen technologies has been fixed exogenously. In a revised model, the user may be equipped with the option of choosing the capacity of the technologies under consideration. Having this feature has several economic benefits. For example, the system planner could base the choice of a technology on the maximum capacity desired of that technology and thus influence the overall capital structure of the microgrid.

While the current analysis is purely deterministic and provides some insights into the portfolio of the technologies to be deployed, the landscape of the technology options may change significantly once demand variability is factored into the model. With changing demand profiles, the model may certainly prescribe more deployment of the dispatchable technologies over the intermittent options. Hedging against uncertainty or changing load or demand will force the model outcome toward less fluctuating sources of supply.

Overall, these improvements when integrated into the current model may lead to significantly different technology profiles. However, the current model is satisfactory enough to tease out the emission and cost implications of different combinations. In the least sense, this could be taken as the commencement of a deeper and more in-depth analysis.

Additional enhancements of the model could include developing a stochastic simulation mode in which costs, revenues, and emissions could be determined for extended time periods (e.g. several years). This would enable the user to estimate average, minimum and maximum costs, revenues, and emission statistics, providing a valuable forecast for microgrid investors. Moreover, a simulation model with a more granular time-step (e.g. hourly) could provide important system information for owners with regard to operations and maintenance of the microgrid.

CONCLUSION

Microgrids have the potential to deliver benefits for the environment, to the power system, and ultimately its customers. They face a number of financial and legal challenges due to their newness and complexity. Providing supportive funding for financial feasibility studies, performing simulation modeling, and establishing public-private partnerships could help overcome financial hurdles and increase deployments. At the same time, a more certain legal framework must be developed to address a range of issues, including a suitable definition, owner rights and obligations, macrogrid connection rules as well as tackling market access, cost and regulatory issues. Additionally, mathematical models can help to more clearly specify and value a microgrid throughout all phases of a project.

Looking ahead, there is much work to do in building awareness about the potential of microgrids as well as how and where they fit into the electricity grid of the future. Also, it will be vital to promote greater dialogue among the finance community, service providers and implementers, government officials at all levels, regulatory agencies, and other stakeholders to develop supportive frameworks and policies. Finally, efforts to improve linear optimization models like the one developed here will help to increase microgrid deployments.

Acknowledgements: Support for this project was made available by the Duke Energy Renewables Innovation Fund at George Washington University. Additionally, the authors would like to thank GWU students Ilka Deluque and Joshua Robichaud for their assistance.

APPENDIX: LINEAR PROGRAMMING MODEL

TABLE A1: NOMENCLATURE

	INDEXES AND PARAMETERS
h	Index for time period (hour)
k	Index to count minimum up or down time for thermal units
i	Index for all technologies considered (Microturbine, Diesel, Gas, Fuel Cell, Solar, Wind, Battery)
j	Index for subset of technologies that exclude battery system (Microturbine, Diesel, Gas, Fuel Cell, Solar, Wind)
e	Index for GHG emissions type (CO_2 , NOx)
TC	Total cost (installation cost + fuel cost + O&M cost) [$]
C_i^{in}	Investment cost of unit i [$/kW]
C_i^F	Fuel cost of unit i [$/MMBtu]
C_i^{OM}	Operation and Maintenance cost of unit i [$/kWh]
C_i^S	Start-up cost of unit i [$]
L_h	Load demand at hour h [kW]
$P_{h,j}^{min}$	Minimum generation power of unit j at hour h [kW]
$P_{h,j}^{max}$	Maximum generation power of unit j at hour h [kW]
P_b^{rated}	Rated Storage capacity of storage system [kW]
soc_{min}	Minimum state of charge of storage system
$\varepsilon_{j,e}$	Factor of emission type e of unit j
R_i	Heat rate of unit i [MMBtu/MWh]
γ_e	Total emissions by type e
α	Price of electricity provided by the grid [$/kWh]
ϵ_e	Factor of emission type e from the grid
T_i^U	Minimum up time for unit i [hours]
T_i^D	Minimum down time for unit i [hours]
UR_i	Ramp rate Up [KW/h]
DR_i	Ramp rate Down [KW/h]
	DECISION VARIABLES
$P_{h,i}$	Generation power of unit i at hour h [kW]
$P_{h,b}$	Charging (-) /Discharging (+) power of storage system at hour h [kW]
$E_{h,b}$	Energy of the storage system at hour h [kW]
P_h^G	Power provided by grid [kW], buy(-); sell(+)
$u_{h,i}$	Binary variable; 1 if unit i is online at hour h, 0 otherwise
$y_{h,i}$	Binary variable; 1 if unit i started-up at hour h, 0 otherwise
$z_{h,i}$	Binary variable; 1 if unit i shut down at hour h, 0 otherwise

MODEL FORMULATION

The goal of the optimization model is to find the generation scheduling over a 24-hour time horizon so that the operational cost can be minimized. The objective function, can be expressed as:

$$\min_{P_i} \sum_{h=1}^{24} \sum_{i=1}^{n} C_i^{in} * u_{h,i} + P_{h,i}(C_i^{OM} + C_i^F * R_i + C_i^S) + \alpha P_h^G \tag{1}$$

Equation is subjected to the following constraints:

System power balance:

$$s.t. \qquad \sum_{i=1}^{n} P_{h,i} = L_h \qquad \forall \;\; h = 1, \dots, 24 \tag{2}$$

The generation power upper and lower bounds of each unit at each hour:

$$P_{h,j}^{min} \leq P_{h,j} \leq P_{h,j}^{max} \qquad \forall \, h, \, j \tag{3}$$

Battery charge and discharge limits:

$$-P_b^{rated} \leq P_{h,b} \leq P_b^{rated} \qquad \forall \, h \tag{4}$$

Hourly state of the battery:

$$E_{h,b} = E_{h-1,b} - P_{h-1,b} \qquad \forall \, h \tag{5}$$

$$SOC_{min} * P_b^{rated} \leq E_{h,b} \leq P_b^{rated} \qquad \forall \, h = 2, \; \dots, 24 \tag{6}$$

$$E_{1,b} = P_b^{rated} \tag{7}$$

Total emissions of the system

$$\gamma_e \leq \sum_{h=1}^{24} \sum_{e=1}^{2} P_{h,j} * \varepsilon_{h,j,e} + P_h^G * \epsilon_e \qquad \forall \, e \tag{8}$$

Start-Up, Shut-Down Constraints

$$P_{h,i} \geq P_{h,i}^{min}\left(u_{h,i} - z_{h+1,i} - y_{h,i}\right) \qquad \forall \, h, \qquad \forall i \tag{9}$$

$$P_{h,i} \leq P_{h,i}^{max}\left(u_{h,i} - z_{h+1,i} - y_{h,i}\right) \qquad \forall \, h, \qquad \forall i \tag{10}$$

Minimum Up and Down times

$$y_{h,i} \leq u_{h+k,i} \qquad \forall \, t, \;\; \forall \, i, \qquad \forall \, k = 1,2, \dots, T_i^U - 1 \tag{11}$$

$$z_{h,i} \leq 1 - u_{h+k,i} \qquad \forall \, t, \;\; \forall \, i, \qquad \forall \, k = 1,2, \dots, T_i^D - 1 \tag{12}$$

Ramp Up and Ramp Down constraints

$$P_{h,i} - P_{h-1,i} \leq UR_i \quad \forall \, h, \qquad \forall i \tag{13}$$

$$P_{h-1,i} - P_{h,i} \leq DR_i \quad \forall \, h, \qquad \forall i \tag{14}$$

TABLE A2: DATA

TECH-NOLOGY	CAPACITY [KW]	FUEL	FUEL COST [US$/MMBTU]	INSTALLED/ CAPITAL COST [$/KW]	HEAT RATE [BTU/KWH]	O&M COST [$/KWH]	NOX EMISSIONS [LB/KWH]	CO_2 EMISSIONS [LB/KWH]
Microtur-bines	1,000	Natural gas	9.32	700–1,100	12,200	0.008–0.01	0.00049	1.19
Diesel generator	6,000	Diesel	15.43	300–800	11,000	0.005–0.015	0.017	1.7
Gas generator	7,000	Natural gas	9.32	300–1,000	9,700	0.007–0.02	0.0059	0.97
Fuel cells	6,000	Natural gas / Hydrogen	9.32	4,000–5,000	6,850	0.0019–0.0153	0.000015	0.85
Photo-voltacis	7,500	Sun	0	4,500–6,000	-	0.0032	0	0
Wind	5,000	Wind	0	800–3,500	-	0.0045	0	0
Battery	5,000	Electricity	0	1,100–1,300	-	0.01	0	0
Grid	5,000	-	-	-	-	0.1258	0.002273	2.149

Sources: Load: GWU one year, hourly load.

Wind: NREL, Transmission Grid Integration. Wind Profile. Eastern Wind Dataset (Hourly). Retrieved from: http://www.nrel.gov/electricity/transmission/wind_integration_dataset.html.

Solar: NREL, Transmission Grid Integration. Solar Power Data for Integration Studies. MD Solar Power Dataset (Hourly). Retrieved from: http://www.nrel.gov/electricity/transmission/solar_integration_dataset.html?disclaimeragreement=This+data+and+software+%28%22Data%22%29+is+provided+by+the+National+Renewable+Energy+Laboratory+%28%22NRE.

Grid: EPA, Energy and Environment. Retrieved from: https://www.epa.gov/energy/egrid.

ENDNOTES

1 U.S. Energy Information Administration, “Carbon dioxide emissions from energy consumption.” Accessed on June 22, 2016. http://www.eia.gov/totalenergy/data/monthly/#environment.

2 U.S. Energy Information Administration, “U.S. energy-related carbon dioxide emissions in 2015 are 12% below their 2005 levels.” May 2016. http://www.eia.gov/todayinenergy/detail.cfm?id=26152.

3 Wood, Elisa, “US Microgrid Market Growing Faster than Previously Thought: New GTM Research.” Greentech Media. August 2016. https://microgridknowledge.com/us-microgrid-market-gtm.

4 U.S. Energy Information Administration, “Electric Power Monthly: Table 6.2A.” Accessed on July 5, 2016. http://205.254.135.7/electricity/monthly/index.cfm.

5 Ibid.

6 Wood, Elisa, “US Microgrid Market Growing Faster than Previously Thought: New GTM Research.” Greentech Media. August 2016. https://microgridknowledge.com/us-microgrid-market-gtm.

7 Ibid.

8 Ibid.

9 Bade, Gavin, “ConEd Brooklyn-Queens non-wire alternative project installs first microgrid.” December 14, 2016. http://www.utilitydive.com/news/coned-brooklyn-queens-non-wire-alternative-project-installs-first-microgrid/432380.

10 Tweed, Katherine, “Con Edison Unveils Auction Numbers for Its Pioneering Demand Management Program in New York.” Greentech Media. August 5, 2016. http://www.greentechmedia.com/articles/read/The-Numbers-Are-In-for-Con-Edisons-Demand-Management-Program.

11 Anderson, Erik, “Microgrids power desert community and urban campus.” Inside Energy. December 21, 2016. http://insideenergy.org/2016/12/21/microgrids-power-desert-community-and-urban-campus.

12 Wood, Elisa, “What Does a Microgrid Cost?” Microgrid Knowledge, April 26, 2016. https://microgridknowledge.com/microgrid-cost.

13 *See, infra,* discussion at n. 51.

14 Wood, Elisa, “Connecticut Figures Out Microgrids (And Helps the Rest of Us) Part 2.” April 7, 2015. http://microgridknowledge.com/connecticut-figures-out-microgrids-and-helps-the-rest-of-us.

15 National Electrical Manufacturers Association, “Microgrids, Macro-Benefits: How to talk to decision makers about building your own electric power system.” 2014. https://www.nema.org/Communications/Documents/Microgrids-Macro-Benefits.pdf.

16 Wood, Elisa, “What Does a Microgrid Cost?” Microgrid Knowledge, April 26, 2016. https://microgridknowledge.com/microgrid-cost.

17 Wood, Elisa, “What Does a Microgrid Cost?” Microgrid Knowledge, April 26, 2016. https://microgridknowledge.com/microgrid-cost.

18 Strahl, Jonathan, “The Bankable Microgrid: Strategies for Financing On-Site Power Generation.” Navigant Consulting. December 2015. http://www.navigant.com/~/media/WWW/Files/PowerGen_BankableMicrogrid_Dec2015.ashx.

19 Wood, Elisa, “Massachusetts Awards $18.4M for Microgrids and other Energy Resiliency Projects.” Microgrid Knowledge, Dec. 29, 2014. http://microgridknowledge.com/massachusetts-awards-18-4m-microgrids-energy-resiliency-projects.

20 Wood, Elisa, “Connecticut Figures Out Microgrids (And Helps the Rest of Us) Part 2.” Microgrid Knowledge, April 7, 2015. http://microgridknowledge.com/connecticut-figures-out-microgrids-and-helps-the-rest-of-us.

21 Wood, Elisa, "California Awards $27.3M for Microgrids and EV Charging Projects." Microgrid Knowledge, Feb. 4, 2015. http://microgridknowledge.com/california-awards-27-3m-microgrids-ev-charging-projects.

22 New York State Energy Research and Development Authority, "Powering a New Generation of Community Energy." Accessed July 5, 2016. http://www.nyserda.ny.gov/All-Programs/Programs/NY-Prize.

23 Wood, Elisa, "New Jersey to Offer Funds for Community Microgrids." Microgrid Knowledge, August 12, 2016. http://microgridknowledge.com/community-microgrids-3.

24 Tweed, Katherine, "New Jersey Launches $200M Energy Resilience Bank for Microgrids and Distributed Generation." Greentech Media (July 24, 2014). Available at http://www.greentechmedia.com/articles/read/New-Jersey-Launches-200M-Energy-Resilience-Bank-For-Microgrids-and-Distrib.

25 Wood, Elisa, "Green Banks to Finance Microgrids?" Microgrid Knowledge (Nov. 2, 2015). http://microgridknowledge.com/green-banks-to-finance-microgrids.

26 Trabish, Herman K., "Public purpose microgrids: Mixed ownership models spur utility investment in growing sector." Utility Dive. August 30, 2016. http://www.utilitydive.com/news/public-purpose-microgrids-mixed-ownership-models-spur-utility-investment-i/425296.

27 World Bank Group, "What are Public Private Partnerships?" October 2015. http://ppp.worldbank.org/public-private-partnership/overview/what-are-public-private-partnerships.

28 Bailey, Carol et al., "Federal Public-Private Partnerships: The Basics of Finance and Why This Is Important to You." Booz Allen Hamilton. December 2014. https://www.boozallen.com/content/dam/boozallen/documents/2015/01/Federal_Public_Private_Partnerships_Viewpoint.pdf

29 Trabish, Herman K., "Public purpose microgrids: Mixed ownership models spur utility investment in growing sector." Utility Dive, August 30, 2016. http://www.utilitydive.com/news/public-purpose-microgrids-mixed-ownership-models-spur-utility-investment-i/425296.

30 Spector, Julian, "Microgrids on the March: Utilities Are Building Out New Business Models to Make Islanding Work." Greentech Media, February 7, 2017. https://www.greentechmedia.com/articles/read/distributech-roundup-microgrids-on-the-march.

31 Frades, Matt et al., "The Role of Clean Energy Banks in Increasing Private Investment in Electric Vehicle Charging Infrastructure." Center for Climate and Energy Solutions. November 2014. http://www.c2es.org/publications/role-clean-energy-banks-increasing-private-investment-electric-vehicle-charging-infrast.

32 Investopedia, "Credit Enhancements." Accessed on January 10, 2017. http://www.investopedia.com/terms/c/creditenhancement.asp.

33 PACE Nation, "Commercial PACE." Accessed on January 10, 2017. http://pacenation.us/commercial-pace.

34 U.S. Department of Energy, "Energy Service Companies." Accessed on January 10, 2017. https://energy.gov/eere/femp/energy-service-companies-0.

35 As defined by Connecticut, "'[m]icrogrid' means a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and that connects and disconnects from such grid to enable it to operate in both grid-connected or island mode." Conn. Gen. Stat. § 16-243y.

36 Connecticut's definition of "Distributed Energy Resource" also includes mention of microgrids. "DER means …. (B) customer-side distributed resource that reduces demand for electricity through conservation and load management, energy storage system which is located on the customer-side of the meter or is connected to the distribution system or microgrid." Conn. Gen. Stat. § 16-1.

37 The Connecticut statutes define a "critical facility" as "any hospital, police station, fire station, water treatment

plant, sewage treatment plant, public shelter, correctional facility or production and transmission facility of a television or radio station, whether broadcast, cable or satellite, licensed by the Federal Communications Commission, any commercial area of a municipality, a municipal center, as identified by the chief elected official of any municipality, or any other facility or area identified by the Department of Energy and Environmental Protection as critical." Conn. Gen. Stat. § 16-243y(2).

38 State utility commissions generally have jurisdiction over distribution level interconnections, although some system owners, such as municipalities, may be exempt from state utility commission oversight.

39 FERC's jurisdiction to impose model interconnection rules extends to "public utilities," which are generally investor-owned utilities. 16 U.S.C. § 824(e) (2017); 18 C.F.R. § 35.28(a),(f). Many utilities not subject to FERC's jurisdiction have elected to adopt open access and interconnection policies that are comparable to those that FERC requires of the public utilities that are subject to its jurisdiction. *See* 18 C.F.R. § 35.28 (e),(f) (2017) (providing for non-jurisdictional utilities to receive approval from FERC of their open-access tariffs, including the interconnection rules).

40 A franchised utility is another way of saying that the utility holds the right to be the exclusive service provider for an area.

41 *See* 18 C.F.R. § 292.305 (2017) (barring rates for sale that discriminate against "qualifying facilities," pursuant the Public Utility Regulatory Policies Act of 1978); *see Alcon (Puerto Rico), Inc.*, 38 FERC ¶ 61,301 at 61,975 (1987) (clarifying that FERC did not find that the pharmaceutical plant that consumed the QF's power was itself a QF, but that "the right to back-up power … covers both the production and consumption functions, irrespective of whether they have the same ownership.") Under a 2005 revision to PURPA, utilities may seek relief from the obligation to buy power from a qualifying facility or sell it power, where the qualifying facility has access to a competitive market.

42 The standards applicable to qualifying small power production facilities and qualifying cogeneration facilities differ, but include size and fuel use for the former and operating and efficiency standards for the latter. *See* 18 C.F.R. §§ 292.203, 292.204.

43 *See, e.g.*, http://www.srpnet.com/prices/priceprocess/customergenerated.aspx (explaining Salt River Project's price plan for solar customers).

44 *See* Case Study, Burrstone Energy Center – Utica NY http://www.powerbycogen.com/burrstone-energy-center (noting that the 3.6 MW CHP-based microgrid has exported over 5 million kWh back to the grid since beginning operations in 2009).

45 "Testimony Of Chantal Hendrzak On Behalf Of PJM Interconnection, L.L.C.," Reliability Technical Conference, Docket No. AD16-15-000, et al., at 5 (2016).

46 *Id.* at 5–6.

47 The North American Electric Reliability Corp. (NERC) establishes standards for the reliable operation of most of the North American electric power grid, subject (in the U.S.) to approval of the standards by FERC.

48 Hendrzak testimony, *Id.* at 6.

49 Iowa Code § 476.25 (establishing exclusive franchise areas for electric utilities). Iowa Admin. Code r. 199-11.1(5) ("An electric franchise shall be required for the construction, operation, and maintenance of any electric line which is capable of operating at 69,000 volts or more outside of cities, except that a franchise is not required for electric lines located entirely within the boundaries of property owned by an electric company or an end user.")

50 Iowa Code § 476.1 ("As used in this chapter, "public utility" shall include any person, partnership, business association, or corporation, domestic or foreign, owning or operating any facilities for … [f]urnishing … electricity to the public for compensation. …This chapter does not apply to …. a person furnishing electricity to five or fewer customers either by secondary line or from an alternate energy production facility or small hydro facility, from electricity that is produced primarily for the person's own use.)

51 *In re* The Baltimore Gas And Electric Company's Request For Approval Of Its Public Purpose Microgrid Proposal, 2016 WL 3941469 at *9 (Md.P.S.C. 2016).

52 *Id.* at *3 (citing PUA § 7-510(c)(6)).

53 *Id.* at *1-2.

54 *Id.* at *2.

55 *Id.* at *5.

56 *Id.*

57 *Id.* at *6.

58 *Id.* at *6.

59 *Id.* at *6-7.

60 *Id.* at *8.

61 *Id.* at *9

62 *See, e.g.,* LA Rev Stat § 45:123 (Louisiana law defining rights to provide electricity, which allows line extensions into unserved areas while preventing new competition in areas with adequate service); Reed Creek Improvement District, https://www.rcid.org/about (explaining the history of the Improvement District, an entity created for the purpose of providing utility and other municipal-type services to Walt Disney World in an area of Florida that was otherwise underserved).

63 *See, e.g.,* Farell, John, "Minnesota's Value of Solar," Institute for Local Self-Reliance (April 2014) Available at: https://ilsr.org/wp-content/uploads/2014/04/MN-Value-of-Solar-from-ILSR.pdf.

64 Overton, Michael L., "Linear Programming." December 1997. https://cs.nyu.edu/overton/g22_lp/encyc/article_web.html.

65 A more complete development of the model and the input data sets would be necessary to produce reliable results. The use cases presented here are for demonstration purposes.

66 Fuel cell technology abbreviations: Molten Carbonate Fuel Cell (MCFC), Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC) and Solid Oxide Fuel Cell (SOFC).

67 Nationwide, power sector emissions are at their lowest level since 1993. "Carbon dioxide emissions from electricity generation in 2015 were lowest since 1993," U.S. Energy Information Administration, last modified May 13, 2016, http://www.eia.gov/todayinenergy/detail.php?id=26232.

CENTER FOR CLIMATE
AND ENERGY SOLUTIONS

2101 WILSON BLVD. SUITE 550 ARLINGTON, VA 22201 703-516-4146 **C2ES.ORG**