



Wealth Creation in Rural Communities

Distributing Electric Energy in Rural America Efficiently and Economically: The Micro-grid Option

by Alisha Fernandez and Seth Blumsack
Penn State University

May 2010

supported by the Ford Foundation

PENNSTATE



Wealth Creation in Rural America

This report is part of the Wealth Creation in Rural America initiative, funded by the Ford Foundation. The aim of the initiative is to help low-wealth rural areas overcome their isolation and integrate into regional economies in ways that increase their own-ership and influence over various kinds of wealth. The initiative has produced nine previous papers, which can be found at <http://www.yellowwood.org/wealthcreation.aspx>. The goal of this report is to advance the initiative's broad aim of creating a comprehensive framework of community ownership and wealth control models that enhance the social, ecological, and economic well-being of rural areas.

The Authors

Alisha Fernandez is a doctoral student in the Department of Energy and Mineral Engineering, College of Earth and Mineral Sciences, Penn State.

Seth Blumsack is assistant professor of energy and mineral engineering in the College of Earth and Mineral Sciences at Penn State. He teaches courses in the energy business and finance program, and in public policy and economics. Dr. Blumsack's research interests include: energy and electrical power systems; network and graph theory; regulatory economics and policy; antitrust and competition policy; market power in electricity markets; and environmental risk and decision making.

Copyright 2010 The Pennsylvania State University

This publication is available in alternative media on request.

The Pennsylvania State University is committed to the policy that all persons shall have equal access to programs, facilities, admission, and employment without regard to personal characteristics not related to ability, performance, or qualifications as determined by University policy or by state or federal authorities. It is the policy of the University to maintain an academic and work environment free of discrimination, including harassment. The Pennsylvania State University prohibits discrimination and harassment against any person because of age, ancestry, color, disability or handicap, national origin, race, religious creed, sex, sexual orientation, or veteran status. Discrimination or harassment against faculty, staff, or students will not be tolerated at The Pennsylvania State University. Direct all inquiries regarding the non-discrimination policy to the Affirmative Action Director, The Pennsylvania State University, 328 Boucke Building, University Park, PA 16802-2801, Tel 814-865-4700/V, 814-863-1150/TTY. MPC110946

Distributing Electric Energy in Rural America Efficiently and Economically: The Micro-grid Option

Electric power has been the backbone of rural America's economic development since the first power lines were strung along rural landscapes. Since then, rural communities' economic vitality has been interconnected with the steady, cost-effective availability of energy—the power needed to start and maintain industries, communities, and economies. Today, ongoing energy concerns, the advent of future electricity deregulation, aging infrastructure, and the climactic events that often wreak havoc on local electric energy supplies are leading many communities to actively consider options that will ensure stable, efficient, and economical electric energy supplies to the U.S.'s rural regions.

One such conversation is occurring around the location of power transmission distribution systems. In rural regions, the fact of relatively few such generation systems is raising concerns about local and regional impacts from external failures and diminished power supplies. One possible solution: the decentralization of the rural power transmission distribution system via the installation of micro-grids. Micro-grids focus on local power generation and allow smaller grid areas to be separated from the rest of the grid in the event of a failure. Further, micro-grid systems may be powered by an industrial generator or several smaller systems such as photo-voltaic systems or wind generation, and are designed to power one another when needed. When combined with smart grid technology (delivery system supplying electricity from suppliers to consumers using two-way digital technology to control consumer home energy use), electric power may be better controlled and distributed, and more efficient and cost-effective.

The Current State of U.S. Electric Power Supply and Delivery

In the United States and most developed nations, electric power is typically generated using *central-station generators*—power plants large enough to serve hundreds or thousands of customers. These plants are often physically located far from the intended point of consumption. Power from these plants is transported along high-voltage power lines (often covering hundreds of miles), and then delivered to end users via a local low-voltage distribution network. One reason for locating central-station plants far from consumers is that the economics of fuel transportation and the economics of transmission lines generally favor locating power plants close to fuel sources, when possible¹. Environmental concerns and

Today, ongoing energy concerns, the advent of future electricity deregulation, aging infrastructure, and the climactic events that often wreak havoc on local electric energy supplies are leading many communities to actively consider options that will ensure stable, efficient, and economical electric energy supplies to the U.S.'s rural regions.

1. J. Bergerson & L.B. Lave (2005), "Should we transport coal, gas or electricity: cost, efficiency and environmental implications," *Environmental Science and Technology* 39(16), 5905–5910.

other siting difficulties in populated areas have made central-station generators highly costly or even impossible to locate close to consumers.

In the United States, central-station electricity generation is highly dependent on fossil fuels, particularly coal and natural gas. Figure 1a shows the current mix of generation technologies in the U.S. electric power system, while Figure 1b shows how these technologies are being utilized for the generation of electric energy. The cost of fuels, capital, and maintenance all influence the use/frequency of use of generating units. As a result, there is a substantial difference between installed capacity in the U.S. and the generating units or technologies used most intensively to generate electricity.

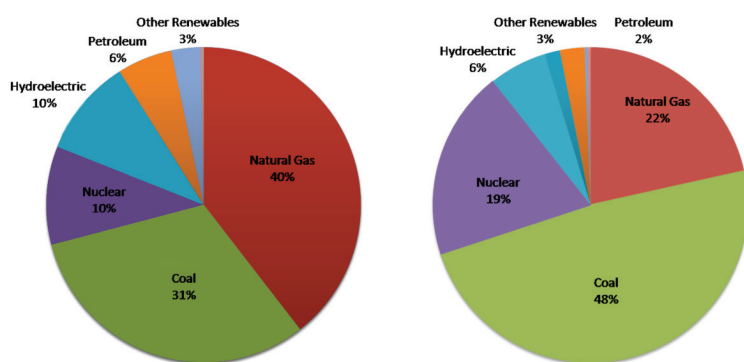


Figure 1. U.S. electric generation capacity (panel [a]) and generation output (panel [b]) by fuel type.

Source: EIA.

Distributed generation (DG) of electric energy to rural areas occurs via small-scale power generation (30 megawatts or less) at a location close to the point of consumption. (One megawatt of electric generation capacity can power 800–1,000 homes.) The U.S. Federal Energy Regulatory Commission defines a small generator as one having a capacity of 20 megawatts (MW) or less. The concept of distributed generation could include a wide range of technologies, from small diesel- or gas-fired plants used by a utility to serve peak electricity demand, to kilowatt-sized photovoltaic or small wind installations serving a single household.

Another factor in the distributed generation conversation is resource control, with some definitions including explicit criteria about control by the owner (owner and end-user are generally assumed to be the same entity) and not by the utility or system operator². Owners may include individual homeowners, office parks, university/hospital campuses, or industrial facilities. Distributed

2. See, e.g., D. King (2005), “The regulatory environment for interconnected electric power micro-grids: insights from state regulatory officials,” Carnegie Mellon Electricity Industry Center Working Paper CEIC-05-08; D. E. King and M. G. Morgan (2003), “Guidance for drafting state legislation to facilitate growth of independent electric power microgrids.” Carnegie Mellon Electricity Industry Center Working Paper CEIC-03-17.

The concept of distributed generation could include a wide range of technologies, from small diesel- or gas-fired plants used by a utility to serve peak electricity demand, to kilowatt-sized photovoltaic or small wind installations serving a single household.

generation resources may be located entirely “behind the meter,” meaning that the power produced is consumed only by the owner of the resource, or that the owner-operator uses the generator as a supplement to grid-powered electricity but cannot control the generator or directly measure its output at any given time.

Distributed generation resources also may be connected to a utility transmission or distribution grid, either through a utility ownership model or a customer-generator ownership model. Typically a customer-generator would not be permitted to connect a distribution generation unit to the transmission grid; access would be limited to the distribution grid³. The interaction between the customer-generator and the distribution grid is regulated on a state-by-state basis through so-called “net metering” regulations and utility tariff provisions. Net metering is discussed in more detail later in this paper.

Recent discussions have focused on distributed generation and micro-grids in rural regions as potential alternative architectures for the production and delivery of electric power.

Alternative Architectures for Electric Power Delivery

Recent discussions have focused on distributed generation and micro-grids in rural regions as potential alternative architectures for the production and delivery of electric power. In these discourses and in general, distributed generation and micro-grids are often used interchangeably. The exact distinction between DG and micro-grids varies, in part because state and federal regulations distinguish between large-scale generation and small-scale generation, or between customer-generators and utility generators. As discussed later in this paper, the lack of a precise regulatory definition for a micro-grid is an often-cited barrier to micro-grid deployment in the U.S.⁴. The CERTS project at the Lawrence Berkeley National Laboratory⁵ has framed the definition of a micro-grid using four criteria:

1. A micro-grid is a co-generation technology; that is, it provides combined heat and power (CHP) services to its customers.
 2. Micro-grids provide these services to “multiple customers connected on a local network.”⁶ Examples might be multiple homes in a residential
-
3. The distinction between the transmission grid and distribution grid is not always uniform or clear. Generally, distribution wires are considered to be those with a voltage rating of 69 kV or less. Transmission networks are generally meshed in nature, while distribution networks are radial (lines in series or parallel configurations). The emergence of electricity deregulation in the U.S. has led to a regulatory distinction between transmission and distribution based on which entity (state or federal) has jurisdiction and rate-making authority over a given line, and whether a given line is subject to federal open-access requirements under FERC Orders 888 and 2000.
 4. King (2005); D. E. King, & M. G. Morgan (2007), “Customer-focused assessment of electric power microgrids,” *Journal of Energy Engineering*, 133:3(150).
 5. http://certs.lbl.gov/CERTS_P_DER.html; see also King (2005); Badami et al. (2008), “Working toward a net-zero energy community: an integrative approach,” Cornell University report for the Kohala Center.
 6. King (2005).

neighborhood or several buildings on a campus or office park property. Inherent to a micro-grid (that may or may not apply to DG) is a non-utility distribution architecture coupled with the power generation resource.

3. The micro-grid is connected to the utility distribution network. Controls and operating protocols govern the interaction between the micro-grid and the utility grid. The utility may be a net supplier of electricity to the micro-grid, or a net buyer of electricity to the micro-grid (or may simply operate independently). Given sufficient metering and control technology, the micro-grid could also independently disconnect from the utility grid in response to a detected disturbance or contingency that would affect reliability of supply for the micro-grid customers or the utility. Thus, the micro-grid could operate in a coupled fashion with the utility grid or could operate as a stand-alone islanded network.
4. Ideally, a micro-grid would fully integrate demand-side response to reduce costs and enhance reliability of the micro-grid.

A micro-grid could be regarded as a specific distributed energy architecture that aims to minimize customer cost and maximize reliability.

Based on these four criteria, a micro-grid could be regarded as a specific distributed energy architecture that aims to minimize customer cost and maximize reliability. Environmental performance has not traditionally played a major role in the definition and analysis of micro-grids, though societal preferences, environmental regulation, and economics have come to change this situation in recent years⁷. The legal and regulatory distinction allowing customer-owned generation but not micro-grids⁸ has also further blurred differences between DG and micro-grid systems.

Micro-grids as an Alternative Architecture for Electric Power

Discussions of alternatives necessarily require comparisons between current practices and potential options. Several factors offer valuable information in the consideration of micro-grids as an alternative to current electric power plants and/or additional stable and efficient source of electric power: costs, size, lifespan, technological advances, and efficiency measures.

COSTS: POWER PLANTS VS. MICRO-GRIDS

The primary drivers of the cost of electric power are capital and fuel. For a large central-station power plant, labor costs are typically less than 10% of electricity

7. The proposed micro-grid community on the Island of Hawai'i is one example. See Badami et al. (2008) for a performance analysis of this system.

8. M.G. Morgan & H. Zerriffi (2002), "The regulatory environment for small independent micro-grid companies," *Electricity Journal*, 52–57.

generating costs. In fact, for a wide range of generating technologies, higher average capital costs are associated with lower variable operating costs. A plant with high average costs will generally require low operating costs to be cost-competitive. The capital costs of power plants are usually reported in dollars per kilowatt, while operating costs are given in cents per kilowatt-hour or dollars per megawatt-hour. The investment cost of a power plant is typically described using an “average overnight” or “levelized” cost. This figure represents the average price charged to consumers for electric power, in cents per kilowatt-hour or dollars per megawatt-hour, needed to break even over a power plant’s lifetime. The levelized cost includes the cost of capital, fuel, and depreciation or amortization over time (and the cost of any emissions permits required to operate the plant, but not necessarily the social cost of environmental impacts).

When we look at micro-grids, we find that their costs are lower because of reduced energy storage, less down time, equipment operating at maximum efficiency, lower hardware expenses, and optimal power input control based on energy costs. Components to add capacity or capabilities may be installed as regions have the resources to adopt them.

SIZE: POWER PLANTS VS. MICRO-GRIDS

Historically, cost has been the greatest barrier to the adoption of distributed generation technologies. At one time, power plants were defined by economies of scale—average (levelized) costs were lower with larger-sized plants. In the 1960s and 1970s, economists estimated the “minimum efficient scale” of a power plant at approximately 200 MW of capacity⁹. Armed with these estimates, utilities built bigger and bigger plants, believing that in doing so they were acting efficiently and saving money for their customers. Today, electricity transmission and distribution by power utilities is still thought to exhibit economies of scale since the average cost of a wire decreases with each additional user on that wire.

There is a great deal of flexibility with the micro-grid architecture—and thus one of its appealing characteristics. Generation within a micro-grid could be a downsized industrial generator or several smaller systems such as photo-voltaic systems, or wind generation. This flexibility allows location in rural regions without substantial cost and the use of a wide range of technologies.

LIFE SPAN: POWER PLANTS VS. MICRO-GRIDS

Power plants are typically long-lived investments. Central-station generators are assumed to have a useful life of perhaps 30 years, but many plants are used for a much longer time (with appropriate upgrades). The average age of

For example, nuclear power plants have capital costs approaching or exceeding \$2,000 per kilowatt but have operating costs of approximately a penny per kilowatt-hour. Natural gas plants, on the other hand, have roughly 25% of the capital costs of a nuclear plant, but fuel alone can cost 6–7 cents per kilowatt-hour. The levelized cost provides a point of comparison for evaluating tradeoffs between capital and operating costs.

9. L. Christensen & W. Greene (1976), “Economies of scale in US electric power generation,” *Journal of Political Economy* 84:4, 655 – 676; J. Johnston (1960), *Statistical Cost Analysis* (New York: McGraw-Hill).

coal-fired power plants in the U.S. is more than 30 years, but some plants have operated for 60 years or longer. The median age of the nuclear fleet in the U.S. is less than 30 years, but nuclear plant lifetimes are expected to be extended to 40 years or longer. State regulators have generally allowed plants to be paid off over 20–30 years, so many of the large power plants currently in operation have no associated capital cost—that is, the costs of these plants represent variable operating costs (primarily fuel) only.

Micro-grids, too, have a long lifespan capacity, depending on configuration and components used, as well as planning undertaken prior to installation with regard to community needs and uses, etc.

TECHNOLOGICAL ADVANCES: POWER PLANTS VS. MICRO-GRIDS

Technological advances also have lowered the cost of distributed generation resources, but the levelized cost of a new DG unit is still higher than the levelized cost of a new central-station generator with an identical fuel source¹⁰. Interconnection costs may create access issues for individuals or communities that are liquidity-constrained and/or operating within strict budget constraints. These costs have not historically been significantly higher for small generators than for large generators¹¹. For many end users, a new distributed generation resource does not compete with a single utility-scale generation facility, but instead with a portfolio of resources that may be offered via the grid. In states with permissive net metering regulations, distributed generation resources may offer an additional source of revenue (from selling excess power to the utility grid) in addition to cost savings for kilowatt-hours of power consumed.

EFFICIENCY MEASURES/COMBINING HEAT AND POWER/ COOLING AND POWER: POWER PLANTS VS. MICRO-GRIDS

The ability to take advantage of combined heat and power (CHP) or combined cooling and power (CCP) increases the overall efficiency of a distributed energy system dramatically. An energy system's efficiency is defined as the ratio of energy input to energy output. The efficiency of power plants is typically measured in terms of a "heat rate"—that is, the amount of fuel required to produce one kilowatt-hour of electric energy. While a typical modern gas-fired combustion turbine might attain 60% efficiency (heat rate of approximately 6,000 BTU per kilowatt-hour), having the ability to capture and use the waste heat for hot water, process heat (or steam), or adsorptive cooling could increase the system's overall efficiency to approximately 90%.

10. King & Morgan (2007).

11. Ibid., based on an assessment of interconnection costs with the PJM system operator in the Mid-Atlantic United States.

With Pennsylvania set to further deregulate the utility industry by lifting rate caps for generating electricity, the price consumers pay for natural gas could go much higher. When the caps come off, a spike in consumer prices is expected, as has already occurred in other states when caps were removed. All this lends urgency to pursuing alternative energy sources.

Smethport, Pennsylvania, is taking a proactive approach with its plan to implement a highly efficient, non-polluting, carbon neutral, CHP system that uses low-value wood as the energy source. Any excess electricity will be put up for sale and distributed over the existing power grid, providing a new revenue stream for the Borough.

WHY SMETHPORT?

Smethport is located in the center of the Pennsylvania Wilds Region, representing 5.2 million acres of forest land. This means that there are plentiful woody biomass feed stocks within the immediate region, including the 500,000 acre Allegheny National Forest and huge tracts of private and state forestland.

Smethport's goal is to facilitate the research and development of a demonstration pilot plant near or within the borough, which will provide carbon neutral, sustainable, locally produced, renewable electric power and auxiliary district heat to borough customers. There is even the possibility of a joint venture between public and private funding sources and ownership. The project is expected to serve as a model for other communities throughout the Commonwealth as well as nationwide.

CHP or CCP is generally more advantageous with distributed generation, since the user controls the waste heat stream, and the heat (in the form of hot water or steam) cannot be transported long distances. Large industrial and commercial users have been utilizing CHP for many years and reporting significant cost savings¹². The Borough of Smethport, Pennsylvania hopes to achieve comparable energy cost savings with a proposed biomass-fired CHP plant and an associated micro-grid¹³.

Estimating the Costs of a Micro-grid System

So how do we assess the cost-competitiveness of a micro-grid system? Again, via comparison—this time by comparing electricity prices per state with the total costs of a micro-grid system. The price of grid-provided electricity is usually the most influential factor in evaluating any cost savings from micro-grids. For certain types of customers in certain locations, micro-grids can reduce total lifetime energy costs by 20–25% compared to grid-powered electricity¹⁴. Savings for customers with access to CHP or CCP have been estimated at 3%–10% annually¹⁵. Typically, the largest economic benefits from micro-grid deployment are attained in areas with high electricity prices and low natural gas prices, though the price of electricity has been found to be a more important determinant of savings than natural gas prices¹⁶.

In order to look at the question of cost-competitiveness, we collected average retail electricity prices for all fifty states from the U.S. Energy Information Administration (EIA)¹⁷. The EIA provides average price information for residential, commercial, and industrial customer classes. A comparative map of average residential electricity prices is shown in Figure 2. Historically, industrial electric rates have been lower than commercial or residential rates¹⁸. The highest residential electric rates have generally been found in the northeastern U.S. and in California. Alaska and Hawai'i also have very high electric rates, due primarily to unique geographic circumstances. Electric rates in some states are not uniform across the state, since some states are served by multiple electric

For certain types of customers in certain locations, micro-grids can reduce total lifetime energy costs by 20–25% compared to grid-powered electricity.

12. See Apt, Blumsack, & Lave (2007) for a discussion relevant specifically to large consumers in Pennsylvania, and Blumsack et al. (2009) for an analysis relevant to small consumers in Pennsylvania.

13. See <http://smethportpa.org/bouroug/green-energy-biomass/>

14. King & Morgan (2007).

15. J. Apt, S. Blumsack, & L.B. Lave (2007), Competitive energy options for Pennsylvania, report prepared for the Team Pennsylvania Foundation.

16. King (2006); King & Morgan (2007); Badami et al. (2008).

17. www.eia.doe.gov/fuelectric

18. The differences in electric rates between customer classes have historically not been correlated with actual costs of service. Industrial and large commercial customers have often been given subsidized rates for job-creation or other economic development purposes.

utilities with different cost structures. For example, the average residential retail rate in Pennsylvania was 11 cents per kilowatt-hour in 2007; in the same year, the average rate for residential customers of the Philadelphia Electric Company was approximately 14 cents per kilowatt-hour,¹⁹ while the average rate for residential Allegheny Power customers was 8 cents per kilowatt-hour.²⁰

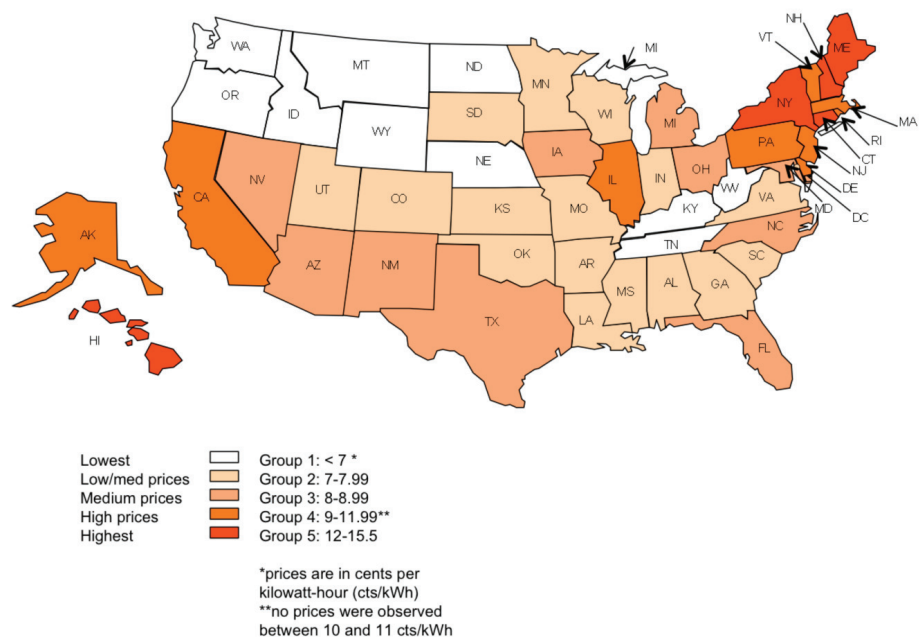


Figure 2: Residential retail electric rates, 1990–2007

(Source: Energy Information Administration).

Deregulation in the electric power sector may also affect the economics of micro-grids. Approximately half of U.S. states, representing almost two-thirds of all electricity consumption, have engaged in some form of electric-industry restructuring. Restructuring has had a significant impact on the pricing of electric power at the retail and wholesale levels. Under regulation, electricity prices were determined on a cost-of-service basis through negotiations and hearings before the relevant state public utility commission. In restructured power markets, generation plants are dispatched by a regional power authority known as a Regional Transmission Operator (RTO) or an Independent System Operator (ISO). The market price of electricity is determined by the cost of the last power plant dispatched to meet demand. Often, this “marginal generator” is fueled by natural gas, which has historically been more expensive than other fuels used to produce electricity. Wholesale power prices have generally exceeded average variable costs of some generating technologies. Thus, a nuclear plant with a cost of \$20 per megawatt-hour (MWh) that would have earned \$20 per MWh

19. http://www.exeloncorp.com/ourcompanies/peco/pecores/energy_rates/our_rates_and_prices.htm

20. <http://www.alleghenypower.com/Tariffs/PA/PATariff.asp>

Electric rates in some states are not uniform across the state, since some states are served by multiple electric utilities with different cost structures. For example, the average residential retail rate in Pennsylvania was 11 cents per kilowatt-hour in 2007; in the same year, the average rate for residential customers of the Philadelphia Electric Company was approximately 14 cents per kilowatt-hour, while the average rate for residential Allegheny Power customers was 8 cents per kilowatt-hour.

under regulation is paid an average of \$60 to \$80 per MWh in a restructured market (earning profits of \$40 to \$60 per MWh). These profits encourage all generating companies to operate more efficiently, but there is some evidence that the deregulated market structure has increased retail prices.²¹ Several states that have transitioned to deregulated retail pricing of electricity have seen rates increase rapidly over a short period of time, with overnight increases of 50% or more. These price increases have been (and continue to be) politically contentious, but since the increases are tied to market structure decisions and not solely to fuel prices, deregulation presents additional economic opportunities for distributed resources and micro-grids.

Electricity prices under deregulation have also been highly volatile and the number of risk-management products available (particularly to smaller consumers) has been limited.²² Self-generation through a micro-grid architecture provides the customer-generator with a hedge against electricity price volatility. The price and cost of micro-grid production at any time are known to the micro-grid owner and end users.

Finally, many generation technologies considered to be viable for micro-grid deployment have relatively low emissions of greenhouse gases or criteria pollutants. Emissions of oxides of sulfur and nitrogen already require permits under the Clean Air Act Amendments of 1990.²³ Power plants in the Northeastern U.S. are already subject to carbon dioxide pricing under the Regional Greenhouse Gas Initiative, and some form of federal climate legislation is increasingly likely. Any comprehensive climate policy at the state, regional, or federal levels will place some sort of price on greenhouse-gas emissions. The regional impacts of carbon pricing will inevitably vary, but on average an emissions price of \$35–\$50 per tonne of carbon dioxide will double the variable operating cost of a coal-fired power plant.²⁴

Electricity prices under deregulation have also been highly volatile and the number of risk-management products available (particularly to smaller consumers) has been limited. Self-generation through a micro-grid architecture provides the customer-generator with a hedge against electricity price volatility. The price and cost of micro-grid production at any time are known to the micro-grid owner and end users.

Other Metrics for Evaluating Micro-grids

Thus far, we've evaluated the micro-grids option according to economic concepts. However, individuals, companies, or communities may have other objectives in mind when assessing distributed energy resources or micro-grids. Some of these objectives may be entirely non-economic (the desire to shift to sustainable energy

21. See Apt (2005); Taber, Chapman, & Mount (2007); and Blumsack, Lave, & Apt (2008). For an opposing view, arguing that retail prices have not significantly increased, see Joskow (2008).

22. Apt et al. (2007).

23. The recently-upheld Clean Air Interstate Rule (CAIR) is likely to tighten annual limits on these pollutants from power generators.

24. Newcomer et al. (2008). This figure assumes a coal plant without any carbon-capture technology; the given price range is an indicator of the carbon price necessary to make capture technologies cost-competitive.

production, regardless of price) or may have an economic value that is difficult to assess.

Let's look at sustainability—a topic of frequent, recent discussion throughout the United States. Sustainability concerns have emerged as an important factor in energy supply choices. Some consumers appear to favor technologies viewed as sustainable or that have low carbon footprints, even when those choices wind up costing more in the end.²⁵ For example, Palamanui, a planned residential community in Hawai'i, has used a “net zero energy demand” principle as a guiding design metric. The community is particularly notable for its planned micro-grid, which integrates electricity supply, storage, demand response and electrified transportation.²⁶

The interconnected nature of power grids means that disturbances or contingencies in one portion of the grid can spread to other portions. The costs associated with blackouts or electric service interruptions are large. The North American blackout of August 2003 was estimated to have cost the U.S. economy \$6–\$10 billion. Energy systems with more distributed architectures have generally been found to be more resilient in the face of attacks, contingencies, or failures.²⁷ A hybrid system of central-station supply and distributed resources can also be used to sustain critical infrastructures in the event of large blackouts.²⁸

Sustainability concerns have emerged as an important factor in energy supply choices. Some consumers appear to favor technologies viewed as sustainable or that have low carbon footprints, even when those choices wind up costing more in the end.

The Changing Regulatory Landscape for Micro-grids

Individual users have embraced the distributed generation option, creating them largely as backups to electricity supplies in the event of outages on the power grid. The use of backup generators has historically been highly restricted. A homeowner may not use a backup generator to supply a neighbor, nor can the homeowner offer to connect a backup generator to the electric grid and then sell the resulting energy to a utility, as entrepreneurial as that may sound. (This last restriction appears not to have been true in New York City, where the utility contracts with some businesses to use their backup generators as a source of peak electricity.) The largest regulatory barrier to the development of micro-grids has

25. For example, waiting lists for the Toyota Prius hybrid sedan are common even though gasoline prices would need to average \$5–\$6/gallon for ten consecutive years to make the purchase of a Prius sensible from a purely economic perspective. See Lave and Maclean (2001). Consumers have been much more economically conservative in purchasing energy-efficiency products for buildings (such as appliances and weatherization); see Howarth and Sanstad (1995).

26. A multi-dimensional analysis of the community concept is provided in Badami et al. (2008). It is worth noting (Thomas, 2008) that regulatory conflicts with the local electric utility related to the micro-grid concept have halted the development's progress.

27. Zerriffi et al. (2005); Apt & Morgan (2005).

28. Apt & Morgan (2005).

been state public utility commissions' belief that the micro-grid network infringes upon the monopoly territory of the distribution utility. The utility is given an exclusive right to serve customers within a given geographic area. This monopoly franchise right may not be interpreted as preventing people from using backup generators or going off the grid entirely, but it does effectively outlaw micro-grids.²⁹ Not only are the owners of distributed generation units not permitted to use a local utility's wires to send power to other end-users, but a micro-grid project may not build its own distribution network.

The murky legal or regulatory definition of a micro-grid has contributed significantly to regulatory uncertainty. Many states distinguish between small and large generator interconnections, but public utility codes are silent on the treatment of micro-grids. Federal regulation also does not distinguish among a micro-grid, a small generator interconnection, and a utility. Such regulatory ambiguity is thus left to be resolved by the regulators themselves. A recent survey of state-level public utility regulators suggested that in a number of states, micro-grids would have the right to exist and operate as long as the micro-grid did not qualify as a "public utility" under that state's public utility code.³⁰ Regulators in these more permissive states have distinguished between a micro-grid and a public utility according to size (number of customers served, megawatts of capacity or both), geographic scope, and ownership (whether the micro-grid owner is also the primary consumer of the electricity).

Interestingly, the Energy Policy Act of 2005 requires every state to consider offering a "net metering" tariff to potential owners of distributed generation. Net metering allows a distributed generation source to connect to the utility's distribution lines and sell excess power to the grid. Thirty-seven states currently allow some form of net metering, although regulations and tariff provisions vary widely across states. The actual tariff provisions offered to net-metered customers vary widely (even within states). The most economically efficient tariff allows a distributed generation owner to charge the market price for every kilowatt-hour of power sold to the utility. However, most net metering tariffs are not set up this way. Some utilities offer to buy net-metered power from distributed generation resources at a fixed rate. In some cases, this fixed rate is on par with local retail or wholesale rates, while in others the fixed net-metered rate is well below wholesale or retail rates. Other utility tariffs only specify exchanges—that is, a kilowatt-hour sold to the utility is treated as a quantity credit on a customer's bill. Exchanges are thus like rolling back the dial on a customer's electric meter.

Both fixed net-metered rate (assuming comparability to prevailing retail or wholesale rates) and quantity exchange can be viewed as second-best substitutes for a market-based net metering tariff, since both compensate power sold to the

The largest regulatory barrier to the development of micro-grids has been state public utility commissions' belief that the micro-grid network infringes upon the monopoly territory of the distribution utility.

29. Zerriffi & Morgan (2002).

30. King (2005). In a number of states a micro-grid would be considered per se illegal, since any networked distributed energy resource would qualify as a public utility.

grid at an identical rate, regardless of time of day or system conditions. Electricity provided to the grid during the afternoon on a hot summer day is invariably more valuable than electricity provided to the grid at 3 a.m. in April. These net-metering tariff policies also create winners and losers in generation technologies. For example, solar photovoltaic power is implicitly penalized under these policies since it tends (or can be configured) to produce more power during times when system demand and market prices are highest.³¹ Wind power, on the other hand, may be implicitly rewarded since wind speeds tend to be highest at dusk and at night, when demands and prices are lowest.

Interconnection standards and regulations are another important factor in assessing state net metering policies. Interconnection standards may present barriers to entry due to high costs or restrictions concerning just when interconnections may be allowed.³² While legal and technical requirements for interconnection vary among states, the majority have poor or non-existent interconnection standards that present barriers to entry for distributed energy resources or micro-grids. This stands in stark contrast to state net metering tariffs, many of which are favorable to micro-grids.

Comparing state policies on distributed generation or micro-grid net metering tariffs and interconnection is an inherently subjective exercise. The Interstate Renewable Energy Council (IREC) has assessed state-level policies relevant to distributed generation and micro-grids.³³ Its assessment categories are reproduced here as Tables 1 and 2. Figures 3 and 4 show the IREC assessments by state. States that have embraced some form of electricity deregulation typically have more permissive net-metering and interconnection regulations than states that have retained a traditional regulated utility structure. From a regulatory perspective, the northeastern U.S. and California appear to be the most advantageous for micro-grid development. The southeastern states, Plains states, Texas, and northern Rocky Mountain states (Idaho, Montana) appear to present the largest regulatory barriers to micro-grids.

While legal and technical requirements for interconnection vary among states, the majority have poor or non-existent interconnection standards that present barriers to entry for distributed energy resources or micro-grids. This stands in stark contrast to state net metering tariffs, many of which are favorable to micro-grids.

31. A rooftop solar panel with a flat orientation will produce the greatest amount of power during the middle of the day, even though system peaks typically occur in the morning and during the late afternoon. Panels can be oriented or creatively designed to match these system peaks. See Brownson et al. (2009).

32. Iowa's definition of a micro-grid as serving no more than five customers is an example of such a barrier; see King (2005).

33. IREC (2008).

Table 1. Guide to net-metering rating criteria.

Source: IREC (2008)

A	Full retail credit with no subtractions. Customers protected from fees and additional charges. Rules actively encourage use of DG.
B	Generally good net metering policies with full retail credit, but there could be certain fees or costs that detract from full retail equivalent value. There may be some obstacles to net metering.
C	Adequate net metering rules, but there could be some significant fees or other obstacles that undercut the value or make the process of net metering more difficult.
D	Poor net metering policies with substantial charges or other hindrances. Many customers will forgo an opportunity to install DG because net metering rules subtract substantial economic value.
F	Net metering policies that deter customer-sited DG, and/or no statewide policy exists.

Table 2. Guide to interconnection procedures rating criteria.

Source: IREC (2008)

A	No restrictions on interconnection of DG systems that meet safety standards. Policies actively facilitate the interconnection of grid-tied customer DG and represent most or all state best practices.
B	Good interconnection rules that incorporate many best practices adopted by states. Few or no customers will be blocked by interconnection barriers. There may be some defects in the standards, such as lack of standardized interconnection agreements and expedited interconnection to networks.
C	Adequate for interconnection, but systems incur higher fees and longer delays than necessary. Some systems will likely be precluded from interconnection because of the remaining barriers in the interconnection rules.
D	Poor interconnection standards that leave in place many needless barriers to interconnection. A few best practices possibly included, but many excluded. A significant number of systems will experience delays and high fees for interconnection, and a sizable percentage may be blocked because of these rules.
F	Interconnection standards include many barriers to interconnection. Few to no generators will experience expedited interconnection, and few to no state best practices are adopted. Many to most DF systems will be blocked from interconnecting because of the standards. This rating also includes no existing statewide policy.

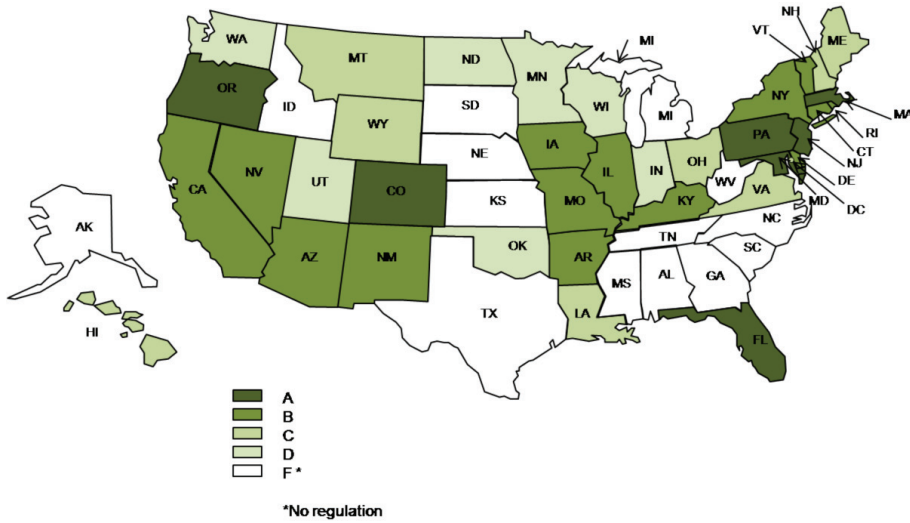


Figure 3. Assessment of state net metering tariffs. An “A” rating indicates the most permissive or advantageous tariff for net-metered DG, while an “F” rating indicates the least permissive or non-existent tariffs for net-metered DG.

Source: IREC (2008)

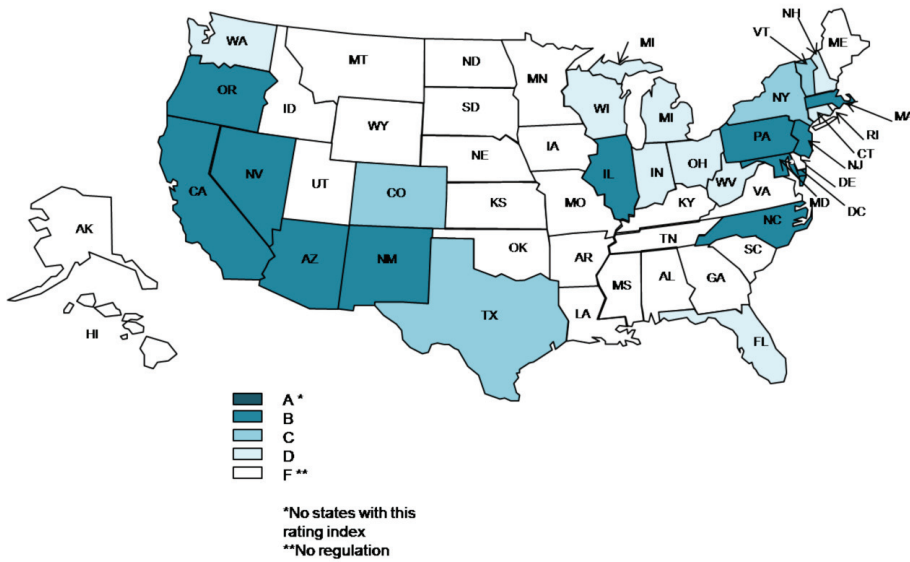


Figure 4. Assessment of state interconnection regulations and protocols for net-metered DG. An “A” rating indicates the most permissive or advantageous interconnection procedures for net-metered DG, while an “F” rating indicates the least permissive or non-existent v for net-metered DG. Note that no state received an “A” for interconnection of DG.

Source: IREC (2008)

Towards an Industry Model for Community-based Micro-grids

No commercial micro-grids are currently operating in the United States, although some pilot projects have been initiated.³⁴ Clearly, there are areas of the U.S. where distributed energy and micro-grids would make economic sense or otherwise be beneficial, but for one reason or another have not yet been deployed. Uncertainty may play a significant role in preventing micro-grid deployment. As with many new or emerging technologies, significant knowledge externalities lead to first-mover disadvantages. Utilities, regulators, and the distributed generation industry face significant learning curves. Profit-oriented firms will prefer to wait for others to experiment and observe those occasions when such experiments went well or poorly.

Despite initial attempts at micro-grid pilot projects, other public demonstration projects may be required to reduce uncertainty and establish an initial business model for the micro-grid industry. The Smethport demonstration project, which will use low-value woody biomass as the primary fuel source, is one possible model of the use of regionally abundant and appropriate fuels. The Hawaiian development of Palamanui provides one potential model for establishing a cost-effective micro-grid based on sustainable energy in a mixed-use residential and commercial community.³⁵ The Palamanui development represents a greenfield approach to micro-grid development—whether a similar sustainable micro-grid architecture makes economic sense in an existing community (where the micro-grid would effectively displace legacy utility infrastructure) is an additional source of economic uncertainty (a micro-grid may be desirable for other reasons). An advantageous legal, regulatory, and economic environment for micro-grids is also required to reduce uncertainty among potential market participants.

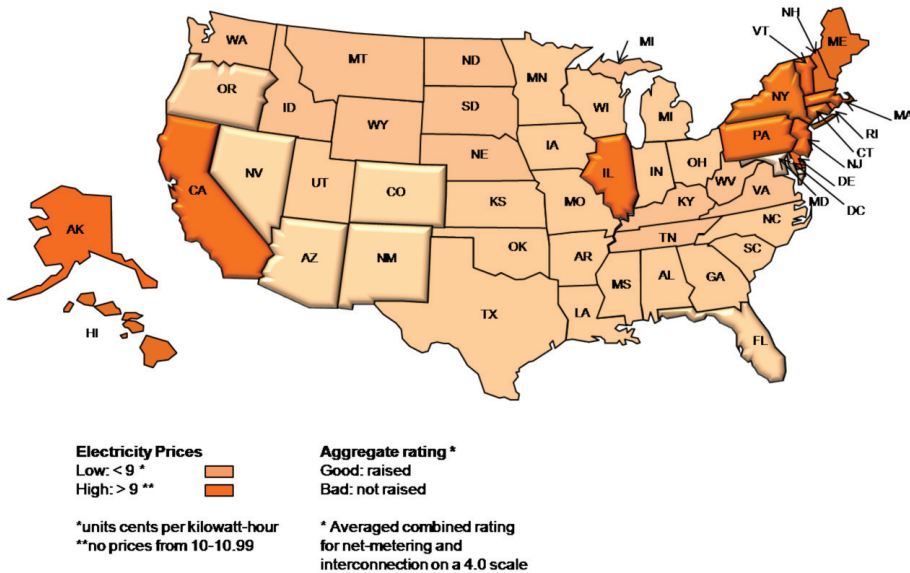
Thus, states with permissive net metering and interconnection regulations and high prices for grid-provided electricity are appealing candidates for micro-grid projects. We have created an aggregate metric for the regulatory environment for grid-interconnected distributed generation in each state. Our metric converts the letter grades used in the IREC report into numbers (A = 4, B = 3, C = 2, D = 1, F = 0), and averages each state's score for net metering and interconnection policy. States with an A, B, or C average are considered to have advantageous policies for micro-grids, while states with an average of D or below are considered to have disadvantageous (or non-existing) policies for micro-grids. We have also divided states into those with high residential electricity prices and low residential electricity prices (more or less than 9 cents per kilowatt-hour). Results are shown graphically in Figure 5.

Clearly, there are areas of the U.S. where distributed energy and micro-grids would make economic sense or otherwise be beneficial, but for one reason or another have not yet been deployed.

States with permissive net metering and interconnection regulations and high prices for grid-provided electricity are appealing candidates for micro-grid projects.

34. Barnes (2005)

35. Badami (2008) and Thomas et al. (2009) both discuss the Palamanui community concept.



States with high electricity prices and highly rated aggregate net-metering and interconnection standards are most likely to invest in a micro-grid since the price of electricity from a micro-grid may be lower than that from a utility.

Figure 5. Assessment of electricity prices and the regulatory environment for net-metered DG. Electricity prices are categorized as “low” or “high,” while the regulatory environment for net-metered DG is assessed by averaging each state’s scores for net metering tariffs and interconnection procedures. States with “good” environments for net-metered DG and high electricity prices are considered to be attractive candidates for micro-grid development; these states are shaded and raised.

States with high electricity prices and highly rated aggregate net-metering and interconnection standards are most likely to invest in a micro-grid since the price of electricity from a micro-grid may be lower than that from a utility. With minimal legal barriers to entry, a micro-grid may be able to connect to the power grid and allow a household or community to more economically manage its energy usage. Most states from Pennsylvania to the Northeast (with the exception of Maine and New Hampshire), and Illinois and California, may be politically and economically advantageous for micro-grid deployment. A number of primarily Western states have utility regulations advantageous to micro-grids but relatively low prices for grid-provided electricity. These states may be advantageous if micro-grid deployment is deemed desirable for reasons other than strict economics. Some of these Western states, such as Oregon, already have low-carbon electricity supplies and so would not face the same level of environmental risk as other states.³⁶

Most states from Pennsylvania to the Northeast (with the exception of Maine and New Hampshire), and Illinois and California, may be politically and economically advantageous for micro-grid deployment.

36. Oregon and Pacific Northwest states are heavily dependent on hydropower for electricity generation. These states will be subject to climate risks related to local hydrological cycles.

A number of different micro-grid industrial and contractual structures have been identified ³⁷:

Utility model—the micro-grid is owned and operated by the distribution utility.

Landlord model or **district heating model**—the micro-grid is owned by a single individual or firm, who provides power and energy services to customers (the “tenants”) under a lease or other long-term contractual arrangement.

Co-op model—the micro-grid is owned and managed cooperatively, with voluntary participation.

Customer-generator model—similar to the landlord model, but the micro-grid is owned by one of the customers.

The primary distinction between the landlord model and the district heating model is that the micro-grid is located on-site in the landlord model (an apartment building, for example) while in the district heating model, the micro-grid may be located relatively remotely to some customers.

Each of these models may be favorable under different circumstances. The utility model, for example, may be least opposed by the public utility regulator. The district heating model has been singled out by regulators as problematic since the firm running the micro-grid is unlikely to be a customer of significant size (thus making the micro-grid operator look more to the regulator like a public utility). The co-op model and the customer-generator model likely fall somewhere in between. A micro-grid project with any of these organizational structures could win approval in the most permissive states (such as Maryland, New Jersey, or Pennsylvania), whereas certain structures would be more difficult to implement in less-permissive states.

Micro-grids as Community Profit Makers

Distribution of wealth from a community micro-grid is an important performance metric, particularly for rural or low-income communities. Large profits earned by generating companies in deregulated electricity markets in California and the Mid-Atlantic have led a number of states to seriously consider re-regulation of their electric sector. Montana and Virginia actually went ahead with re-regulation. If maximizing community benefit is an important policy goal (consistent with goals of energy independence and community development), then the micro-grid industry should display the following characteristics:

- a. A diverse set of firms should be offering “turn-key” systems. Micro-grids are technically complex. The existence of firms offering system-level

37. Terminology from King (2005) and Lassetter et al. (2002) is used in this discussion.

Utility model—the micro-grid is owned and operated by the distribution utility.

Landlord model or district heating model—the micro-grid is owned by a single individual or firm, who provides power and energy services to customers (the “tenants”) under a lease or other long-term contractual arrangement.

Co-op model—the micro-grid is owned and managed cooperatively, with voluntary participation.

Customer-generator model—similar to the landlord model, but the micro-grid is owned by one of the customers.

solutions (rather than individual firms supplying the generator, the substation, and other individual components) will reduce transactions costs for consumers and communities;

- b. A diverse set of local support services should be available. Distributed generation likely exhibits network externalities—the value to customers or community members increases with the number of customers using the product. Installing and maintaining a micro-grid require a diverse skilled labor force, from engineers to HVAC specialists to linemen.
- c. The industry should have knowledge of local conditions. Not all generation sources are feasible or desirable in all locations. Geographic conditions and the existence of a fuel delivery infrastructure are two important considerations. Renewable energy sources may be more advantageous in distinct geographic regions (e.g., solar photovoltaics in the desert Southwest). Natural or bottled gas is readily available in the Northeast (since many households and businesses already use this fuel for heating). Many Northeast locations are also geographically advantageous for sub-utility-scale wind installations (e.g., the ridges of Pennsylvania and the southern tier of New York).

These characteristics may be desirable, but are not descriptive of the current distributed generation industry. The industry is currently very fragmented, with firms specializing in individual technologies rather than systems. The distribution portion of the micro-grid industry is still generally controlled by the utility, although a number of non-utility firms that provide transmission and distribution services to the utility industry (such as ABB or Black & Veatch) could find additional markets serving the micro-grid industry. The distributed generation industry is also in a young, formative, and chaotic stage. Some technologies (particularly small-scale wind and solar photovoltaics) are seeing large numbers of firms enter the market, but few new entrants appear to have contracts or a saleable product. Given the technological sophistication and manufacturing capabilities required, some degree of concentration or shake-out is inevitable.

Micro-grids and Employment Opportunities

A local workforce for micro-grid installation and maintenance may be yet another benefit. In very rural or remote locations, a local workforce is necessary to support a community micro-grid investment. The skills necessary to install and maintain a micro-grid's complex equipment are in short supply, even for the utility industry. Identifying local workers with complementary skills will be critical. Some state and university training programs have emerged that focus on training electricians, roofers, and other contractors to install backup generators and renewable energy supplies for single-customer generators. The missing piece to support a micro-grid industry through similar programs is training in the installation of local distribution equipment.

Conclusion: The Economic, Environmental, and Equity Value of Micro-grids

The U.S. electricity industry is made up of a patchwork of utility companies operating under local, state, and federal regulations and prices. While distributed generation via a micro-grid system offers important, stable opportunities for generating and managing electricity production and consumption at the community level, functional commercial micro-grid systems are not currently available in the U.S., in part due to the endurance of the long-standing legacy of the monopoly utility system. For nearly a century, power utilities have largely determined and controlled each state's legal rights to power production and technical rights to connect to a transmission or distribution grid. This legacy clearly presents barriers to the implementation of alternative power production and delivery systems like the micro-grid.

Universities and other research organizations can play an important role in defining and assessing the shape of the future micro-grid industry. Possible models might be energy service companies (ESCOs) or existing district heating companies. ESCOs have typically signed contracts with individual customers rather than groups of customers or cooperatives of customers, but they already provide a number of installation and maintenance services (HVAC, for example) relevant to a high-value micro-grid industry. District heating companies already exist in the U.S., primarily in urban areas. The local network served by a district heating company is similar in scope to the network that would be served by a micro-grid.

In summary, since conversations among policy and other decision makers on topics like energy resources and alternatives typically include a look at the economics, impact, and equity of available options, we conclude with such a look here (with impact in this case centering on the environment).

ECONOMICS

As we've seen, if electricity prices are high and natural gas prices are low, micro-grids can save money for participating customers. The regulatory barriers to micro-grid development are still strong in many states despite policy initiatives intended to support micro-grids and distributed generation. Regulatory permissiveness thus acts as a third criterion for a micro-grid to be economically beneficial. We have categorized states based on electricity prices and regulations relevant to micro-grid development (see Figure 5). States with the highest residential electricity prices included the northeast United States (such as New York, New Hampshire, Maine and Massachusetts) and California. States with an advantageous regulatory environment also included the Northeast (e.g., Massachusetts, Maryland, and Pennsylvania) and Oregon. Given the current regulatory ratings and electricity prices in the U.S., the states that seem likely to

The regulatory barriers to micro-grid development are still strong in many states despite policy initiatives intended to support micro-grids and distributed generation.

approve community micro-grids are primarily in the Northeast (Pennsylvania, New Jersey, Massachusetts, or New York) as well as Illinois and California.

ENVIRONMENT

Micro-grids may emit high or low amounts of greenhouse gases or criteria pollutants (including particulates), depending on the energy source utilized. Communities seeking to establish micro-grids based on environmental objectives should consider the life-cycle environmental implications of any proposed system, including the emissions impact of any power source used to back-up variable generation. The community micro-grid model will generally have two distinct environmental advantages over central-station generation systems. First, the use of waste heat from power generation for CHP or CCP can significantly improve operating efficiency and environmental performance. Second, the demand side is more highly integrated into the operation of the energy system in a micro-grid architecture. Individuals can clearly see the value of energy-efficient behaviors, while community efficiency goals can be reflected in how the micro-grid system is planned and operated.

EQUITY

Micro-grid development, if done in an economically advantageous location and setting, will reduce the amount of community wealth spent on utility grid power or fossil fuels to heat homes and businesses. This means that energy-related support services (fuel delivery companies, local linemen working for the utility, and others) may suffer. At the same time, the distributed generation industry in the U.S. is not mature (much less so the micro-grid industry). If community development or wealth-creation is an important goal in the installation of a micro-grid, an investment in physical capital will almost certainly need to be accompanied by an investment in human capital for installation, maintenance, support, and managerial services.

Micro-grids may emit high or low amounts of greenhouse gases or criteria pollutants (including particulates), depending on the energy source utilized. Communities seeking to establish micro-grids based on environmental objectives should consider the life-cycle environmental implications of any proposed system, including the emissions impact of any power source used to back-up variable generation.

Micro-grid development, if done in an economically advantageous location and setting, will reduce the amount of community wealth spent on utility grid power or fossil fuels to heat homes and businesses.

Bibliography

- Apt, J., 2005. "Competition has not lowered US industrial electricity prices," *Electricity Journal* 18(2): 52–61.
- Apt, J. & M.G. Morgan, 2005. "Critical electric power issues in Pennsylvania," report prepared for the Pennsylvania Department of Environmental Protection, available at www.cmu.edu/electricity.
- Apt, J., S. Blumsack, & L.B. Lave, 2007. "Competitive energy options for Pennsylvania," report prepared for the Team Pennsylvania foundation, available at www.cmu.edu/electricity
- Badami, V., J. Bride, N. Ceci, S. Day, J. Fike, M. Fradette, B. Jonsson, A. Melvin, R. Olpadwala, C. Onwuchekwa, C. Persheff, P. Seiper, C. St. John, L. Swanson, M. Bohm, M. Miller, R. Thomas, & M. Zhang, 2008. "Working toward a net-zero energy community: an integrative approach," Cornell University report for the Kohala Center.
- Barnes, M., 2005. "Micro-grid laboratory facilities," *Proc. 2005 International Conference on Future Power Systems*, Amsterdam, The Netherlands.
- Bergerson, J. & L.B. Lave, 2005. "Should we transport coal, gas or electricity: cost, efficiency and environmental implications," *Environmental Science and Technology* 39:16, pp. 5905–5910.
- Blumsack, S., L.B. Lave, & J. Apt, 2008. "Prices and costs for electric utilities under regulation and restructuring," Carnegie Mellon Electricity Industry Center working paper CEIC-08-03, available at www.cmu.edu/electricity.
- Blumsack, S., J. Brownson, & L. Witmer, 2009. "Economic and Environmental Performance of Ground-Source Heat Pumps in Central Pennsylvania," *Proc. of the 42nd Hawaii International Conference on System Sciences*, Waikoloa HI.
- Brownson, J., S. Blumsack, & J. Rayl, 2009. "Matching photovoltaic orientation to energy loads," *Proc. of the American Solar Energy Society*, Buffalo NY.
- Chambers, A., 2001. *Distributed Generation: A Non-Technical Guide*, PennWell, Tulsa OK, 283 pp.
- Christensen, L. & W. Greene, 1976. "Economies of scale in US electric power generation," *Journal of Political Economy* 84:4, pp. 655–676.
- Dondi, P., D. Bayoumi, C. Haederli, D. Julian, & M. Suter, 2002. "Network integration of distributed power generation," *Journal of Power Sources* 106, pp. 1–9.
- Howarth, R. & A. Sanstad. "Discount Rates and Energy Efficiency," *Contemporary Economic Policy* 13:3 (1995), pp. 101–103.
- Interstate Renewable Energy Council (IREC), 2008. "Freeing the Grid: Best and worst practices in state net metering policies and interconnection standards," available at http://www.newenergychoices.org/uploads/FreeingTheGrid2008_report.pdf
- Johnston, J., 1960. *Statistical Cost Analysis*, McGraw-Hill, New York.
- King, D., 2005. "The regulatory environment for interconnected electric power micro-grids: insights from state regulatory officials," Carnegie Mellon Electricity Industry Center working paper CEIC-05-08, available at www.cmu.edu/electricity.
- King, D., 2006. "Electric power micro-grids: opportunities and challenges for an emerging distributed energy architecture," Ph.D. Dissertation, Carnegie Mellon University.
- King, D.E. & Morgan, M.G., 2003. "Guidance for drafting state legislation to facilitate growth of independent electric power microgrids." Carnegie Mellon Electricity Industry Center working paper CEIC-03-17, available at www.cmu.edu/electricity.
- King, D.E. & Morgan, M.G., 2007. "Customer-focused assessment of electric power microgrids." *Journal of Energy Engineering*. DOI: 10.1061/(ASCE)0733-9402(2007)133:3(150).
- Lasseter, R., A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromson, A. Meliopoulos, R. Yinger, & J. Eto, 2002. "The Integration of Distributed Resources," California Energy Commission report P500-03-089F.
- Lave, L.B. & H. Maclean, 2001. "Are Hybrid Vehicles Worth It?" *IEEE Spectrum*, March, pp. 47–50.
- Morgan, M.G. & H. Zerriffi, 2002. "The regulatory environment for small independent micro-grid companies," *Electricity Journal*, pp. 52–57.

Pepermans, G. & J. Driesen, 2005. "Distributed generation: definition, benefits and issues," *Energy Policy* 33, pp. 787–798.

Taber, J., D. Chapman, & T. Mount, 2006. "The Effects of ISO Auction Markets on Retail Electricity Prices," Cornell University Applied Economics working paper.

Thomas, R., K. Zhang, M. Bohm, & M. Miller, 2009. "An Integrated Design Approach for Sustainable Community Development," *Proc. of the 42nd Hawaii International Conference on System Sciences*, Waikoloa HI.

Zerriffi, H., H. Dowlatabadi, & A. Farrell, 2005. "Incorporating stress in electric power systems reliability models," *Energy Policy* 35:1, pp. 61–75.