Policymaking for Microgrids

Economic and Regulatory Issues of Microgrid Implementation

TECHNICALLY, MICROGRIDS ARE EMERGING AS AN OUTGROWTH OF DISPERSED on-site and embedded generation via the application of emerging technologies, especially power electronic interfaces and modern controls, and, similarly, microgrid economic and regulatory analysis is generally rooted in the same approaches used to evaluate distributed energy resources (DER). As in the economics of many traditional on-site generation projects, the economics of heat recovery and its application by combined heat and power (CHP) systems is central to the evaluation of microgrids, and integration of this capability is a key requirement whenever CHP appears as an option. The recovery of waste heat offers a key advantage to generation close to loads but at the same time adds significantly to analysis complexity because of the need to simultaneously meet requirements for electricity and heat, plus the inevitability of storage, both active and passive, entering the equation. More novel is the economics of power quality and reliability (PQR), which in microgrids can potentially be tailored to the requirements of end uses in a manner only considered to a limited degree in utility-scale system; e.g., by interruptible tariff options. The economics of microgrids arises from evaluation methods for on-site generation from the customer perspective and from the traditional utility economics of expansion planning from the utility perspective. Both of these areas have received considerable attention, so a growing toolkit exists, but methods need reinforcement in some key regards. Central to public policymaking will be consideration of the societal impact of microgrids, especially since their adoption may change macrogrid requirements. While partially explored, this topic is still in need of rigorous analysis.

Setting the Scene

Big Picture Economics

Cost-reflective pricing mechanisms are critically important to facilitating competition in generation. In the context of the impact on network costs, this is manifested in the cumulative value chain from

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power generation to consumption. Electricity produced by large central generation is sold in European wholesale markets for around 3–5 EURcent/kWh, but by the time this electricity reaches the end consumer it is being sold at a retail price of 10–15 EURcent/kWh. This increase in value is driven by the added cost of transmission and distribution services to transport electricity from the point of production to consumption. Note that most of these costs occur at the point of interface between the macrogrid and the customer through metering and billing, customer services, storm recovery, etc. Despite its critical effect on economics, this point is often overlooked in discussions of the relative efficiency and cost of small- versus large-scale generation, the practical limitations on the possible beneficial application of CHP, and the high cost and low power density of renewable resources. Conversely, it is often argued that if utility customers are free to self-generate or not at will, they are not paying the full costs of their burden on the macrogrid, as is further discussed below.

One of the central conceptual promises of microgrids is that multiple decision-making responsibilities may be concentrated in the hands of one agent, thereby removing one of the serious causes of market failure in existing centralized power systems, most clearly evident in underinvestment in energy efficient equipment. In other words, imagine a single decision maker being responsible for purchasing commercial energy inputs, grid power, generator fuels, and generating equipment, and at the same time being responsible for choosing end-use equipment, storage technology, and potentially taking advantage of any local opportunity fuels such as solar or a bio waste stream. Perhaps this omnipotent decision maker will trade off these complex alternatives in the evenhanded manner that has escaped us heretofore, resulting in chronic underinvestment in energy efficiency. For example, with a payback of months in some applications, compact fluorescent light bulbs still command only about 5% of the U.S. market. Similarly, small-scale renewables and storage technologies have been slow to penetrate the market in part because they often lie beneath the radar screens of utility planners. Successfully combating climate change will require us to overcome these past failings, and microgrids offer one promising opportunity for achieving a wiser future. Part of the analysis challenge, therefore, is to develop methods and tools that can guide developers of microgrids toward desirable decision-making at both the design and operating stages. Further, the desirable outcomes might involve complex combinations of technologies and behaviors. While economic methods for evaluation of on-site electricity supply and CHP are well developed, areas in need of research attention remain. In general, past analysis of CHP has relied on rather simplistic technical rules of thumb and inadequate consideration of the importance of complex market incentives such as time-of-use or feed-in tariffs. More specifically, microgrids bring to the fore the issues of waste-heat-driven cooling, on-site energy storage, and heterogeneous PQR, which are all relatively uncharted areas of engineering-economic analysis.

> The economics of microgrids arises from evaluation methods for on-site generation for the customer perspective and from traditional expansion planning for the utility perspective.

Importance of Building Cooling

The growth of building cooling requirements with its consequent effect on peak load growth, system investment requirements, and electricity supply reliability has been an area of concern in most parts of North America and Japan for some time; increasingly the warmer areas of Europe face similar concerns. In Greece, the summer peaks in 2005, 2006, and 2007 exceeded their corresponding winter peaks by approximately 10%, 15%, and 20%, respectively, and in 2004 and 2006, Spain experienced winter peaks only about 5% larger than its summer peaks. Further, if climate change brings occasional hot summers, such as France experienced in 2003, spurts of air conditioning adoption may severely tax macrogrids. Further, France's heat wave simultaneously caused low river flows that reduced hydro generation and limited nuclear output because of reduced cooling capacity. These developments enhance the argument for local provision of electricity service to vital services and the use of CHP systems to provide building cooling, which lowers peak electrical loads. This possibility poses some new challenges because it creates a simultaneous effect in which the recovery of waste heat from on-site generation lowers the requirement for generation and, in fact, for capacity along the whole supply chain. Further, cooling of buildings can be achieved using a host of approaches: passive cooling, traditional electrically powered compressor air conditioning, direct-drive equivalents, absorption cycle technology using either direct fire or waste heat, passive methods, precooling using building thermal mass, etc. Designing microgrids such that waste heat is effectively utilized poses a challenge in general, and the addition of this cooling complication significantly adds to the burden. Note, however, the importance of waste heat recovery from the energy efficiency (or, equivalently, climate change) perspective. Currently, the waste heat emitted from U.S. power plants is responsible for approximately 28% of the energy-related carbon emissions of the country. This is of the same order as all transportation sector emissions, which currently represent about 32%. Further, the waste-heat-related emissions are growing as electricity becomes a more dominant fuel, and more of the generation mix is thermal generation, which means that if current trends continue, transportation will be overtaken by waste heat as a source of carbon emissions in five years or so.

Storage

Economic evaluation of electrical, thermal, or fuel storage always poses a complex problem because of its inter-temporal nature, i.e., the way storage is operated in any time step affects its operation in many others, and because of the need to make decisions despite uncertainty surrounding future circumstances. Deployment of electrical storage on large scales is limited, e.g., in pumped hydro stations, although combustion fuels are stored in massive quantities, e.g., in natural gas tanks. The waste heat from thermal power generation is almost never stored on a large scale. Microgrids bring all these aspects of the storage problem together. If load variation, supply intermittency, or hard economics require it, local electrical storage is a promising option for microgrids, particularly given the emergence of new battery technologies, such as flow batteries. Because, in most instances, heat and electrical loads do not occur together, heat storage may also be attractive. For example, an office building may need considerable electricity throughout the day but space heating primarily during the morning hours when occupants arrive for work and/or cooling during hot afternoon hours. Storage may be active using specific devices, such as fluid tanks, or may be passive, such as by precooling or heating of a building to take advantage of its thermal lag. Additionally, because a key objective of microgrids may frequently be to provide reliable power during grid outages and because these may accompany disruptions in fuel supplies, on-site storage of fuel(s) may also be desirable.

Power Quality and Reliability

An important aspect of microgrid economics that has minimal evaluation methods available is local control of PQR. The tradition in electricity supply has been one of universal standards for PQR. While not necessarily achieved in practice, the paradigm for control of PQR has been to strive for the same standard in all parts of the supply network at all times. Achieving the targets has incurred both physical and operational costs; i.e., maintaining and improving PQR require both investment in equipment and redundancy but also conservative operating procedures that preclude some economic transactions, with consequences costly to societies. Microgrids create an opportunity for a radical rethinking of this paradigm. By sophisticated local control by a microgrid, the prospect of tailoring PQR to match the requirements of end-uses becomes a promising source of economic gain. Note that many end-use loads need only low PQR, and the ones that do require gourmet power are typically small. Matching PQR requirements more precisely than is done today might yield considerable benefits. Further, multiple PQR supplies might be delivered to various parts of a single device. Analysis approaches to determining the desirable level of PQR either globally in the macrogrid or locally in the microgrid simply do not exist.

The Complex Regulatory Environment

The regulatory environment into which microgrids are entering is extremely complex, in part because they encroach on multiple areas of existing regulation not conceived with them in mind, i.e., generator interconnection rules, air quality permitting, building codes, tariffication, etc.

Traditional interconnection rules required generators to trip in the event of any disturbance, while one of the key objectives of microgrid development is to achieve systems that can island and ride through grid problems, or in some proposals partially so. Clearly, a conflict exists. Through considerable effort in IEEE committees, proposed rules are emerging to overcome the problem. Operating parts of the distribution network or customer sites in island mode, i.e., isolated from the upstream network, with the voltage and frequency regulated locally by resources outside the jurisdiction of the utility may also create conflicts with existing codes and regulations. Safety and damage liability issues also may arise since the distribution utility may no longer be responsible for the operation of the island.

In general, market mechanisms are still not mature enough to accommodate the envisaged participation of microgrid entities. Where feed-in tariffs exist, they are usually fixed for small-scale DER, often based on the primary energy source, while the retail consumer kWh tariffs in many countries are centrally regulated. Metering issues also need to be resolved, since current regulatory practice requires metering energy at the connection point of each individual user, rather than at the aggregation point of user groups.

A European View

Fundamental to development of European energy policy has been the move toward liberalized competitive markets that support and promote the development of cost-effective future systems, together with a significant emphasis on climate change policy that requires cutting greenhouse gas emissions from the power sector. There is a clear focus in the European Union on promoting low-carbon generation technologies and renewables with a new and binding target of a 20% renewable portfolio standard by 2020. Over the last decade, this policy commitment has been matched with national incentive schemes and support mechanisms for renewable and low-carbon distributed energy sources that have contributed to a reduction in technology costs and an increasing penetration of smaller-scale generation into distribution networks.

In this context, more recently there has been an increased interest in various forms of microgeneration, primarily in small-scale and domestic CHP and photovoltaics (PV). In Germany, more than 1.5 GW of PV has been installed in residential and commercial sectors as a result of favorable tariffs. Another interesting example is that the Woking Borough Council installed the first local-authority-private-wire CHP system in the United Kingdom, providing heating to civic offices, a local parking lot, two hotels, and leisure centers. Woking installed 1.5-MW and 950-kW CHP systems with thermal storage and heat-activated absorption cooling together with a 200-kW fuel cell with CHP and a number of PV panels. The system can island, and is operated by an energy service company that is involved in the operations, the investment in primary energy plant (boilers and chillers) and their eventual replacement, electricity and heat distribution, and supply of green energy direct to customers. Such developments have in turn raised the question of (in)appropriateness of the existing technical, commercial, and regulatory framework to support cost-effective integration of these emerging generation technologies into overall system operation and development. Based on Woking's success, the London Climate Change Agency has recently been established to accelerate reductions in London's greenhouse gas emissions. The new agency aims to deliver low- and zero-carbon energy projects and services involving a combination of energy efficiency; combined cooling, heating, and power; renewables; and other innovative technology including waste-, water-, and transport-related projects. One of the showcase projects is London City Hall (Figure 1), which features 617 PV modules with peak capacity of 52.4 kW installed on the domed roof and 46 bespoke translucent glass-glass laminates with peak capacity of 14.6 kW forming an "eyelash" that provides solar shading for the ninth floor (London's Living Room). There are over 28,000 individual PV cells with a total active area of 417 m^2. The system is expected to generate about 50,000 kWh of electricity each year, i.e., 1.5% of City Hall's current total energy consumption, and save over 28,000 kg of CO_2 each year.

figure 1. London City Hall.

Economics

Microgrid Perspective: A U.S. Example

As mentioned above, the economics of microgrids from the customer perspective arises out of the evaluation of on-site and embedded generation. However, the participants in a

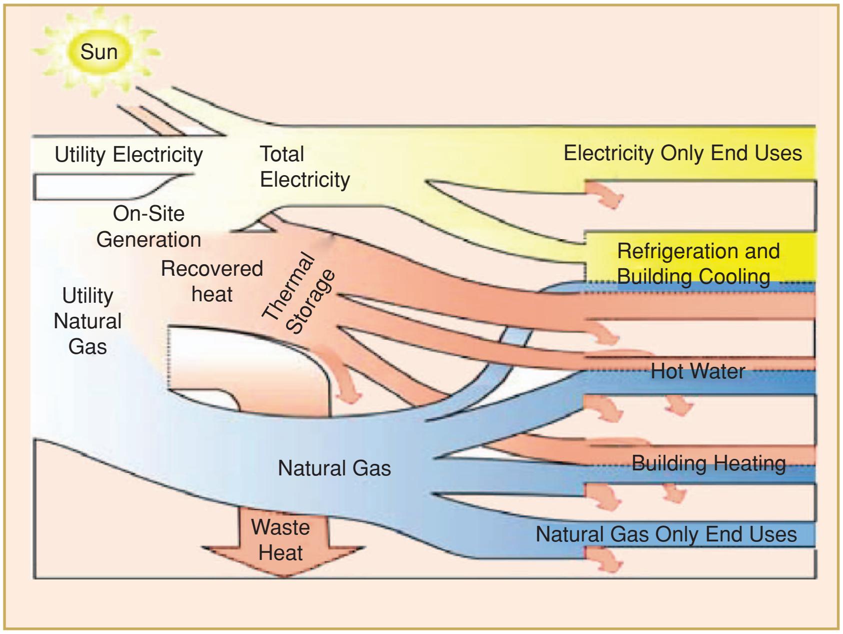

figure 2. Energy flows in a microgrid from fuels to end uses.

microgrid are not customers in the traditional sense; rather, they are a grouping of coordinated sources and sinks that are operating in unison, so they appear to the utility as a single entity, either a net source or net sink. Coordination here goes beyond simply acting as a group. The microgrid is closer to an integrated energy system designed and operated to meet the energy requirement (electrical, heating, and cooling) of its members as well as to supply electricity of PQR commensurate with the requirements of end-use loads.

One notable research effort in the United States to develop methods for the evaluation of microgrids is the Distributed Energy Resources Customer Adoption Model (DER-CAM), which has emerged from the Consortium for Electric Reliability Solutions (CERTS) research program funded by the U.S. Department of Energy (USDOE) and the California Energy Commission (CEC). It identifies optimal technology-neutral DER investments and operating schedules at a given site, based on available DER equipment options and their associated capital and O&M costs, customer load profiles, energy tariff structures, and fuel prices. The Sankey diagram in Figure 2 shows partially disaggregated microgrid end uses on the right-hand side and energy inputs on the left. DER-CAM solves this entire problem optimally and systemically, finding the combination of equipment and their operating schedules that meet the load requirements. The goal function is typically cost minimization, but carbon minimization or other objectives are possible.

Figure 3 and Figure 4 show some example results from DER-CAM for a hypothetical San Francisco, California, hotel with 25,000 m^2 of floor space. This is a contrived example in which storage has been made available at low cost to demonstrate the potential complexity of solutions. The optimal system chosen for this site consists of a 200-kW natural-gas-fired reciprocating engine (gas engine) with heat recovery, a 722-kW solar thermal array that augments engine heat recovery, a 585-kW absorption chiller, 1,100 kWh of electrical storage, and 299 kWh of heat storage. In Figure 3, the pink line shows the true hourly heat demand of the hotel, which is only for water heating on this summer day. The black line shows the heat load including the heat used for cooling, which is the difference between the two curves. When total heat production goes above the black line, storage is being charged, while the purple colored area represents heat recovery from storage. Note that heat is supplied from two sources: CHP heat recovery from the gas engine and, during the daytime, solar thermal collection. Figure 4 shows the electricity balance on the same day. Similarly, the pink line shows actual electricity requirements, while the black line is the actual requirement plus electricity demand that has been displaced by absorption cooling as represented by the dark blue striped area. Note that a considerable fraction of electricity is still purchased from the utility, although the generator runs at close to its maximum of 200 kW for most of the day. The electricity storage is used to supplement supply during the expensive daytime hours (1200 to 1800 are the local on-peak tariff hours).

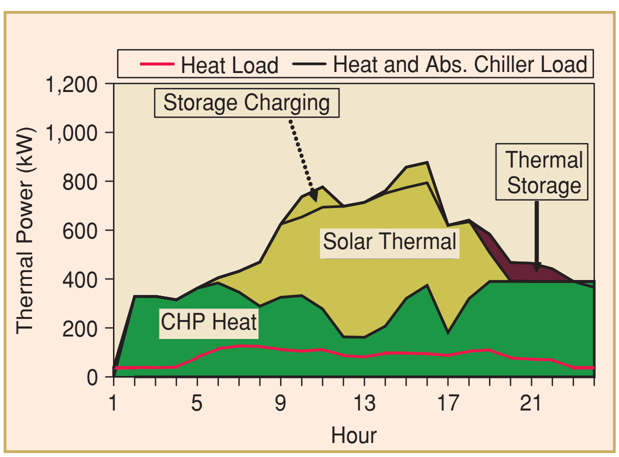

figure 3. Heat balance for a July weekday (source: CERTS).

Microgrid Perspective: A Japan Example

A similar approach to DER-CAM's has been applied to some potential microgrid host sites in Japan. Three microgrid hosts are assumed, as shown in Table 1; the first one (No. 1) includes a mixed office and apartment building; the second one (No. 2) is a hospital, also with apartments; and the third (No. 3) consists of a hotel with office and retail space. The peak summer demand of all three hosts is about 1 MW.

This work has found that the optimal number of gas engines selected is determined by the ratio between baseload and peak electricity demand together with the ratio between heat and electricity demand. As the ratio of baseload to peak increases, the number of gas engines selected decreases because larger units have higher energy conversion efficiency. Technological advances in gas engines have been significant—overall thermal efficiency is now at least 40% (lower heating value), i.e., higher than the typical 350-kW class gas engine currently used in power generation systems. Figure 5 shows the scale economy of energy conversion efficiency (y-axis) of a gas engine (plotted at load factors of 50%, 75%, and 100%).

Some battery storage is required to supply electricity for a limited time during the peak demand period, and a thermal storage tank for space cooling and space heating is selected to minimize the use of a direct natural-gas-fired absorption chiller. Figure 6 shows the results for a winter day.

The same research has considered the beneficial effects of customer load aggregation. For example, when a hotel, retail store, and office operate their own gas engines, it requires five units, and an average of 32.5% is achieved. If loads are aggregated, the total number of units can be reduced to two, and average generating efficiency is improved to 37.6%, while annual cost is reduced by 4.5%. Conversely, depending on a smaller number of units reduces redundancy and therefore reliability, which creates a complex trade-off in actual applications.

Utility Perspective: An Unlikely Beginning

Interestingly, at least one outstanding example of the initial innovative conceptual thinking about a more dispersed electricity supply system came from the utility perspective. Around 1990, researchers at the Pacific Gas and Electric (PG&E) research laboratory in San

table 1. Host configurations for case studies.

No.	Configuration	Total Floor Area [m^2]	Ratio of Off-Peak Demand to On-Peak Demand: Electricity	Ratio Between Heat and Electricity Demand
1	Office	25,000	0.350	1.01
	Apartment	42,000		
2	Hospital	29,000	0.278	1.57
	Apartment	20,500		
3	Hotel	8,000		
	Retail	3,000	0.213	1.18
	Office	20,000		

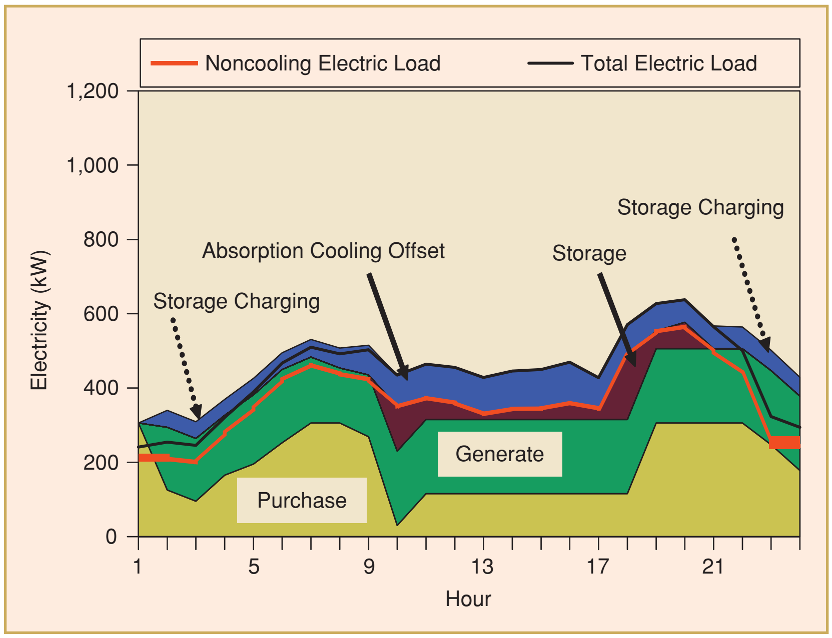

figure 4. Electricity balance for a July weekday (source: CERTS).

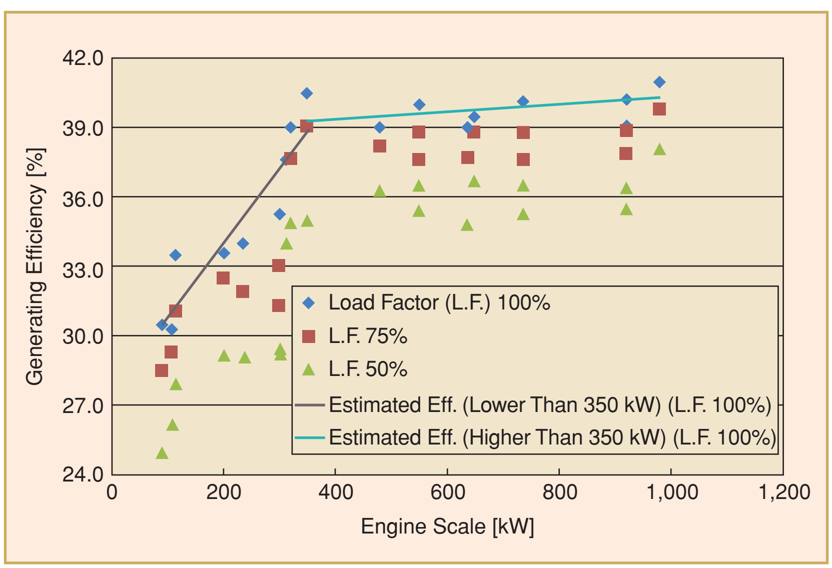

figure 5. Scale economy of generating efficiency of a gas engine (source: University of Tokyo).

Ramon, California, began to explore the possibility of using PV deployment as a way to postpone expansion of the distribution system, especially substations. The investigators observed that the load on the distribution infrastructure is highly peaky where air conditioning is prevalent, and all elements of the supply chain must be sized to meet the peak. In fact, in California, air conditioning contributes about 14% to the state's annual peak, while it is only responsible for about 5% of the electricity consumption. Further, in the hot interior parts of the state, peaks occur on hot sunny afternoons when PV output could be confidently relied upon. Using fortuitously available data for a 500-kW PV installation planned for an area near a saturated 10.5-MW substation, the benefit-cost ratio of such an installation to delay necessary system upgrades was estimated.

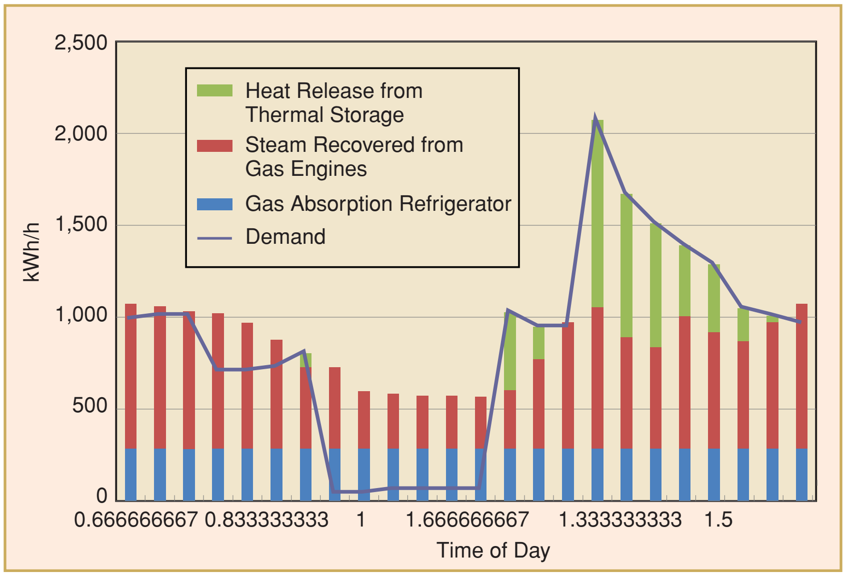

figure 6. Space-heating demand and supply for a winter weekday (source: University of Tokyo).

At the time, the PG&E work found that the PV option was not competitive, but its researchers' innovative thinking kicked off a new line of reasoning that has ultimately led to questioning of the fundamental logic of the entire centralized power system, most notably in developing economies where the legacy grid is weak or nonexistent. Locally in northern California, methods for valuing dispersed deployment of renewables in some local distribution networks have now reached a high stage of development. One study has developed a method for assessing the benefits of distributed generation (DG) systemwide for some local utilities. The relevance of this body of work is in part that the value of sources or net load reductions in the current supply system could provide a revenue stream for microgrids if they are independent entities and incentives to utilities to develop microgrids themselves. Current pricing of electricity, as discussed below, typically tends to be constant over large areas, but this consistency is an artifact of the regulatory process and does not deliver accurate price signals to customers in most cases. Particularly, the added costs of delivering power to congested areas and those where the infrastructure is reaching limits are not reflected in prices.

Utility Perspective: Avoided Cost Estimation

Microgeneration, located close to demand, delivers electricity directly with limited requirement for use of the network. This power may therefore have a higher value than that of conventional generation due to the potential of DG to reduce the demand for distribution and transmission network capacity, reduce losses, and, if integrated, increase the reliability of supply seen by the end customers. The importance of understanding and quantifying these benefits has been recognized, although these are yet to be incorporated within the technical, commercial, and regulatory framework. Clearly, ignoring these particular features in the derivation of the value of microgeneration results in noncompetitive markets in which small-scale generation cannot compete on a level playing field with conventional generation. Ultimately, this will create inefficient and non-cost-reflective systems, whereby microgeneration is not efficiently integrated into the system, and the resulting framework relies on unnecessary network reinforcement and inefficient solutions based on increasingly expensive, low-utilization conventional generation.

The potential benefits and costs of integration of PV and micro CHP into system operation and development will be driven by a number of factors including:

- ✔ level of penetration
- ✔ density (distribution)
- ✔ correlation between generation operation patterns and demand profiles.

Regarding the impact on networks, given that microgeneration is located near load, this will result in reduction of losses and release of network capacity, which can be used to defer future network reinforcement needed to accommodate load growth.

In Southern Europe for example, where peak demand occurs on hot summer days, PV generation is likely to reduce losses in distribution networks. In this context, it is important to remember that losses are a quadratic function of load, and so most losses occur in summer daytime as this is the most heavily loaded time for the majority of networks. This coincides with the expected operation of PV, and the loading on the network and losses will therefore be reduced. The results of studies carried out on some typical networks for different levels of penetration are presented in Figure 7.

The reduction of losses is expressed as a percentage of the base losses that are the distribution losses with no PV

> If load variation, supply intermittency, or hard economics require it, local electrical storage is a promising option for microgrids, particularly given the emergence of new battery technologies.

installed in the system. It can be concluded that PV can make a very significant contribution to loss reduction; especially in long rural distribution networks (up to 40%).

In Northern Europe, on the other hand, there has been increased interest in the network benefits of the application of micro CHP. Again, the operation of CHP tends to coincide with peak demand that occurs on winter evenings. Studies carried out on typical U.K. distribution networks show similar trends: the reduction in network losses driven by micro CHP could reach between 25% in urban and 40% in rural systems, which is clearly very significant. On the other hand, installation of PV in Northern Europe will tend to have less beneficial impact given winter-driven peak demand. The estimated maximum loss reduction could be between 10% and 20%.

Regarding the benefits from realizing network capacity by reducing peak demand, studies on the U.K. distribution network suggest that the value of savings in future network reinforcement and replacements enabled by domestic CHP could be worth up to about €150 /kW of microgeneration connected. Furthermore, increased reliability of electricity supply created by microgrids that are capable of operating in an islanding mode could be significant given that faults in medium-voltage distribution networks are responsible for the vast majority of interruptions seen by end consumers. Studies conducted in the United Kingdom indicate that the economic benefit of the reliability improvement would be about €30 per domestic consumer (and significantly more for commercial customers).

Another important benefit of domestic CHP is in its contribution to reduction of the amount of conventional generation capacity required to meet system peak demand, given that the output is typically coincident with the winter peak. This effectively reduces the demand at the winter peak seen by the rest of generation, thus reducing the capacity required to maintain system security. Averaged across many CHP units, this effect would be fairly predictable and reliable, so domestic CHP could actually displace existing conventional generation capacity. Given that, typically, energy displaced by domestic CHP is smaller than the conventional capacity displaced, this creates savings that are estimated at 2 €c/kWh produced by CHP.

However, turning these economic benefits created by microgrids into commercial income will require significant changes in the regulatory framework, and this transition is in its infancy.

Societal Perspective

Considerable analytic efforts have been made to portray the full societal balance sheet for distributed power systems, but considerable challenges remain nonetheless. An outstanding example is the 2002 book *Small Is Profitable* by Amory Lovins. This book represents a heroic effort to collect all the information pertinent to development of a dispersed system into one volume and make the definitive case for a distributed system.

Another notable effort to describe a few of the societal benefits of a dispersed power system was produced by the USDOE last summer. Among discussion of other benefits, the study reports on outstanding examples of DG providing improved resilience to vital services. For example, the Mississippi Baptist Medical Center was able to operate as an island for 52 hours following Hurricane Katrina using its on-site 3.2-MW turbine. It was the only hospital in the area able to maintain full-service operation. Under normal operating conditions, the system provides 80% of total electricity, 95% of steam, and 75% of cooling using two absorption chillers.

Regulation

The issue of interconnection pervades all sizes of independent generation, but it becomes most problematic for relatively small-scale operations, for which the cost of complex engineering studies and/or special equipment would be prohibitive. Here DER more generally have blazed the trail for microgrids;

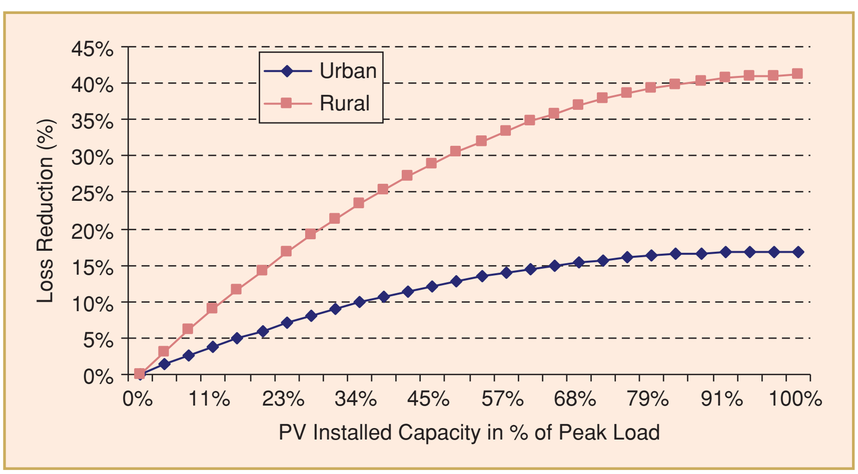

figure 7. Reduction in losses as a function of PV generation penetration.

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however, microgrids raise some particular technical issues. Most notably, they are intended to operate as islands and may additionally be controlling PQR semi-autonomously, whereas many interconnection rules require DER to disconnect in the event of a disturbance.

Interconnection: Europe

In Europe, DER interconnection rules are typically set at the national level by macrogrid technical regulations, regulator directives, or national standards. Regardless of the normative procedures applied, interconnection practices aim to ensure that DER will not disturb other users of the network in normal operation, and that safety will not be jeopardized in case of abnormal conditions. To this end, interconnection procedures typically include technical provisions on the following:

- ✔ voltage regulation and power quality, including steady-state voltage deviations, fast variations, flicker, harmonics, dc injection
- ✔ power factor
- ✔ protection and anti-islanding schemes
- ✔ earthing-grounding arrangements.

Although country-specific variations do exist, interconnection practices and rules invariably treat DER as a potential source of disturbance for the network, an attitude related to and originating from the traditional unidirectional operating paradigm of radial distribution networks. This attitude is best reflected in the anti-islanding provisions of all existing European codes, which force immediate disconnection during blackout to prevent potential safety threats to other network users and utility field crews, as well as to avoid operation and protection complexities. Anti-islanding is realized via passive or active protection schemes. Passive anti-islanding protection typically utilizes voltage and frequency relays at the installed DER terminals that determine whether island conditions exist. Active anti-islanding capabilities common in inverter-connected DER are based on more sophisticated and robust algorithms for detecting loss of grid conditions. In all cases, DER are forced to quickly disconnect (in times ranging from a tenth of a second to a few seconds), precluding the possibility of DER supporting its local part of the grid. Once a DER unit has disconnected from the network, it cannot reconnect into a deenergized system.

Although current grid codes do not permit the formation of islands within the distribution network, they do permit intentional islanding of user facilities; i.e., the separation of a specific private installation from the public network to improve its own PQR. This can be accomplished if the user installation includes suitable DER resources and the interconnection is designed to provide backup islands during network outages. This approach requires, besides sufficient and reliable embedded generation to support local load, careful coordination with utility sectionalizing and protection equipment. Upon occurrence of upstream network faults or outages, the installation isolates from the network, forming an island, which is supported by local generation (and possibly storage), self-providing frequency, and voltage regulation. To return from island to grid-connected mode, suitable synchronizing equipment is required. Such an approach is compatible with microgrids, which typically apply intentional islanding and controlled reconnection of one self-controlled microgrid or of one comprising several coordinated users.

To establish a framework suitable for the development and proliferation of microgrids in Europe, the overall interconnection framework needs to be revised, taking the following specific issues into account.

- ✔ During islanding, micro sources will operate in a confined network with drastically altered characteristics while performing active regulation and control duties.
- ✔ Deliberate islanding of network sections without loss of local generation should be permitted while penalizing unintentional (and potentially harmful) islanding. Note that the overcurrent protection typically installed at the connection point of every network user may no longer be effective in the islanded mode of operation due to the low fault currents expected.
- ✔ The standardization of network components and construction will also need to change for sections of the network where microgrid operation is foreseen. This would require the installation of controllable interconnection breakers and paralleling means at the point of coupling of the whole microgrid, e.g., at the low-voltage busbars of a distribution substation, where fuses would normally suffice. Modified network protection devices might be required within a microgrid section, along with specific provisions for neutral earthing upon isolation from the main grid. Suitable communication infrastructure running along with the power lines might also be needed. In general, distribution utilities will have to modify their overall network development practices where the formation of microgrids is foreseen.
- ✔ Finally, metering arrangements will also need to be modified. The installation of a simple meter per user

installation will no longer suffice. Additional metering of incoming and outgoing power and energy will be required at the overall microgrid point of common coupling, while more sophisticated metering tools will definitely be required to support the participation of the microgrid in markets.

Interconnection: Japan

In Japan, the Ministry of Economy, Trade, and Industry (METI) has established rules and technical guidelines for grid interconnection. As amended in 2004, these rules regulate safety and assure power quality in Japan's highly reliable network. METI's rules establish technical standards for electric equipment under the Electricity Industry Law. Requirements include relays, switches for protection, islanding prevention, and communication systems. The technical guidelines for power quality govern interconnection in the low-voltage (100–200 V), high-voltage (6–22 kV), and extra-high-voltage ($>$ 22 kV) networks and include voltage regulation limits; e.g., 101 $\pm$ 6 V, 202 $\pm$ 20 V for low-voltage distribution lines and voltage dips under 10% are limited to 2 s. However, these rules contain no provisions on cost bearing among parties, which may cause problems. For example, excess voltage outside the required range is expected after the first connection between a distributed generator and the distribution line goes smoothly. The grid connection might be based on a first-come, first-served basis and cannot produce social-optimum penetration of distributed generators. Furthermore, it is necessary to unify the standards required for interconnecting distributed generators with information and distribution networks. Implementing control and protection of distributed generators as good citizens that needs a two-way communication system between distributed generators and the system operator.

Interconnection: The United States

Early U.S. research showed that interconnection barriers are significant and costly. Released in 2000, one influential study interviewed developers who had attempted to interconnect new technologies at customer sites. Of the 65 projects reviewed, only seven were interconnected in a timely manner. Concern about barriers to distributed power has led to considerable efforts to enable lower hassle and cost of interconnection. As with many U.S. regulatory issues, interconnection is seriously complicated because utility regulation resides, in large part, at the state level. Within the United States, therefore, the progress of interconnection regulation is quite uneven. Certain states have moved ahead, which in some cases has involved legislative action.

In 2003, after five years of development, the *IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems* was published with the goal of creating a set of technical requirements that could be used by all parties on a national basis. During IEEE 1547 development, it was recognized that islanding parts of the distribution system, depending on implementation, could improve reliability or, if unplanned, be a serious problem. The concepts of intentional and unintentional islanding were developed and defined in the standard. IEEE 1547 addresses unintentional islanding by requiring the DR to detect the island condition and cease to energize the area electric power system (EPS) within 2 s of island formation. Although it was realized that intentional islanding (microgrids) could be beneficial to distribution system and customer reliability, this issue was deferred for consideration in future revisions of the standard. In late 2003, IEEE formed a new project under the IEEE 1547 series to address intentional islanding and microgrids called *IEEE P1547.4 Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems.* Currently in draft, this document will cover microgrids and intentional islands that contain DR connected at a facility level and with the local utility. It provides alternative approaches and good practices for the design, operation, and integration of the microgrids and covers the ability to separate from and reconnect to part of the utility while providing power to the islanded local power systems. The guide will cover the DR, interconnection systems, and participating electric power systems. It is intended for use by designers, operators, system integrators, and equipment manufacturers. Its implementation will expand the benefits of DR by enabling improved EPS reliability and building on the requirements of IEEE 1547.

figure 8. Hachinohe street showing parallel public and private distribution feeders.

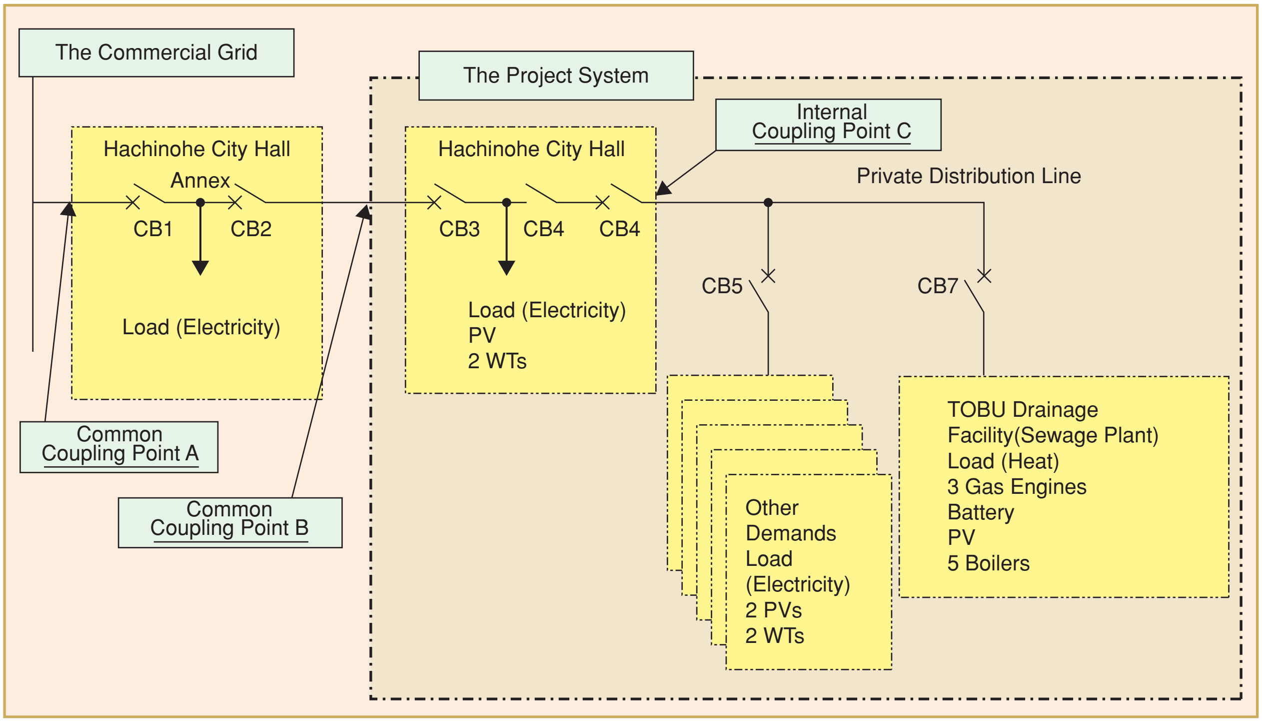

figure 9. Main loads in the Hachinohe microgrid and its macrogrid interconnection.

Macrogrid-Utility Interaction at a Demonstration in Japan

An indicative problem between the microgrid and its local macrogrid has been experienced during a New Energy and Industrial Technology Development Organization (NEDO)-funded microgrid demonstration project in Hachinohe, northern Hokkaido. This project began operation in October 2005 and is being evaluated for PQR, cost effectiveness, and carbon-emissions reduction over its demonstration period, which ended in March 2008. The microgrid has PV and wind turbines totaling 100 kW, 510 kW of controllable gas engines supplied by digester gas from a sewage plant, and a 100-kW lead-acid battery bank. Seven Hachinohe City buildings are supplied via a private 6-kV, 5.4-km distribution feeder (shown in Figure 8), with the whole system connected to the commercial grid at two nearby points of common coupling at City Hall and its annex building. Test islanding operation was also demonstrated at this project.

Figure 9 shows a schematic of the project, and Figure 10 shows the main site. This water treatment plant contains the biogas digestor with waste-wood-fired heat, the biogas engines, and a battery bank.

Under an agreement with the local utility company, electricity can serve the City Hall and annex buildings, the largest microgrid users, but is not allowed to flow into the private distribution line at internal (not common) coupling point C, so a reverse power relay is installed there. The under-power relay at coupling point A between the commercial grid and Hachinohe City Hall and the reverse power relay at coupling point C have a reaction time of 1 or 2 s. Unfortunately, the relays may activate in the event of fluctuations caused by the starting or stopping of large electrical equipment during low demand periods, especially at night. This situation has created a costly hard constraint on operation of the microgrid. As in many microgrid demonstrations in Japan, a constant power flow at the coupling point was a major objective of the Hachinohe demonstration and has been successfully achieved, although by application of complex microgrid controls. In this case, a harsh

figure 10. Central generation facility at the Hachinohe water treatment plant.

As with many U.S. regulatory issues, interconnection is seriously complicated because utility regulation resides, in large part, at the state level.

requirement was placed on the microgrid with serious economic consequences, so further deregulation of electricity markets might reduce the risk of these operational constraints. Analysis of the control strategy will be carried out to determine its impact on operating cost. A more economic control strategy would certainly have reduced the necessary battery and reserve capacities.

Environmental Regulation

Even though small-scale power generation accounts for a tiny share of urban pollution compared to mobile sources, since the two are sometimes regulated differently, microgrids might be severely disadvantaged. This is the case in California where only about 3% of urban nitrogen oxide and minimal hydrocarbon emissions are derived from any form of generation, with the overwhelming majority of emissions coming from vehicles. Yet, small generators are soon to be subject to very strict standards, set statewide for microturbines and fuel cells but locally for gas engines, and further, California's legislated objective of reducing the state's greenhouse gas emissions to 1990 levels by 2020 stands in conflict with prevailing urban air quality rules, which are likely to impede the development of microgrids that could improve the utilization of fossil fuels overall.

The division of authority in California between stationary sources and mobile sources has caused a major imbalance in the weight of regulation on the two pollution sources. One possible form of redress would be to regulate based on overall footprint rather than stack emission rates. A microgrid may involve thermal generation, but at the same time, use of CHP, renewable generation, and efficient end-use devices may mean that the total footprint of the microgrid is lower than the macrogrid alternative. If standards were set on this basis, a more desirable overall outcome might be achieved.

Conclusions

Some aspects of microgrids represent a radical departure from existing approaches to provision of electricity, while others are outgrowths of existing systems, or even returns to ways of doing business commonplace to the industry during bygone times. Developing economic and regulatory methods to accommodate them will require us to look in many places for inspiration and tools. In some areas a solid basis is in place while elsewhere we still face challenges.

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For Further Reading

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