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ABSTRACT

The blackouts of summer 2003 underscored the dependence of western economies on reliable supply of electricity with tight tolerances of quality. While demand for electricity continues to grow, expansion of the traditional electricity supply system is constrained and is unlikely to keep pace with the growing thirst western economies have for electricity. Furthermore, no compelling case has been made that perpetual improvement in the overall power quality and reliability (PQR) delivered is possible or desirable. An alternative path to providing for sensitive loads is to provide for generation close to them. This would alleviate the pressure for endless improvement in grid PQR and might allow the establishment of a sounder economically based level of universal grid service.

Providing for loads by means of local power generation is becoming increasingly competitive with central station generation for a number of reasons, four key ones being non-technical constraints on expansion of the grid, improvements in small scale technologies, opportunities for CHP application, and the ubiquitous nature of sensitive loads in advanced economies. Along with these new technologies, concepts for operating them partially under local control in microgrids are emerging, the CERTS Microgrid being one example. It has been demonstrated in simulation, and a laboratory test of a three microturbine system is planned for early 2005, to be followed by a field demonstration. A systemic energy analysis of a southern California naval base building demonstrates a current economic on-site power opportunity.

Introduction

The August 2003 blackout underlined North America’s dependence on its imperfect power grid(s). Analyses conducted in the aftermath have focused almost exclusively on ways to perfect the grid, presuming highly developed economies require flawless power at whatever cost. As our impressive and successful modern grids have evolved, the expectation that they can and should be uniformly close to perfect has led to a system of critically interdependent services vulnerable to grid failure. Heightened security concerns and the penetration of electronics into myriad aspects of everyday life are deepening this vulnerability.

Some less explored solutions to grid vulnerability are: (1) providing heterogeneous power quality and reliability (PQR), so that quality provided better matches quality needed; (2) hardening socio-technical systems to an inevitably imperfect grid; or (3) providing power sources locally to sensitive loads. Considering alternatives is vital, as the technologically advanced economies struggle to meet inexorably growing electricity usage and push the limits of affordable power quality.

While dependency on the grid has intensified, smaller generation using a diverse mix of technologies, usually collectively called distributed energy resources (DER), has emerged as increasingly competitive with large remote central station generation. Many of these sources generate power directly, e.g. photovoltaic modules (PV), while others involve on-site energy conversion. Waste heat utilization delivers one of the key advantages of small scale generation involving conversion, e.g. from reciprocating engines, fuel cells, or microturbines. This heat can be productively applied to many end-uses, but when used for cooling, using absorption cycles, it can be particularly valuable because it displaces high priced electricity and simultaneously lowers the peak power requirement of the site, i.e. both saves expensive on-peak electricity and downsizes other system requirements.

A rich and growing literature explores the case for supplementing our existing power system by smaller scale localized generation closer to loads. The purpose here is not to provide a comprehensive survey of DER benefits, although a brief survey is offered. Rather, just two issues are addressed: (1) the inability of our existing power system to provide for growing electricity use together with the inappropriateness of providing for the most demanding end-uses by a universal standard PQR, and (2) the potential benefits provided by application of combined heat and power systems in microgrids. A description of a specific microgrid concept under development, the CERTS Microgrid, is presented along with an example analysis of a potential southern California microgrid host.

Third-World Grid

At lunchtime on 14 August 2003, incorrect data were entered into system monitoring software at the MISO headquarters in Carmel IN, rendering it ineffective (OTF 2003). The vast, sprawling, discontinuous 2.8e6 km^2 (1.1 million square miles) territory MISO controls, spanning states from North Dakota almost to the East Coast, was unwittingly jeopardized. Failure to properly respond effectively to the fairly routine events that followed during that afternoon degraded much of the MISO system to a point, around 3:45 pm, when the system was beyond recovery. Following loss of a large line just after 4:00 pm, major cascading failures over a major area of the northeast left about 50 million people in the U.S. and Canada surviving in a darkened, dangerous, hobbled economy. Luckily, aside from the economic losses, the consequences of this blackout were not major, but the illconceived interdependency of many of our critical systems became painfully apparent: mobile phone systems fell silent; the Toronto subway stayed parked for 3 days. While such dramatic blackouts are rare, the last events on a comparable scale in the U.S. being the California blackouts during the summer of 1996, the northeast U.S. blackout was soon coincidentally followed by large scale outages in London, Scandinavia, and Italy (UCTE 2004). In all these cases, the vulnerability of advanced economies to blackouts was further underscored.

Interestingly, developing countries appear more robust against power failures and poor power quality, an advantage achieved by the utilization of storage technologies, tolerance for power quality excursions, retention of manually-operated alternatives, and widely accepted behavioral responses to failures. Many commentators claimed the northeast blackout was evidence that the U.S. has a “third-world grid” (Firestone and Pérez-Peña 2003).[1] Actually, the reverse best describes our developed economy vulnerability to power loss. In large part because we have a reliable *first-world* grid, we expect near perfect power everywhere at all times. Places that cope with unreliable power systems survive power outages better. They are less vulnerable in large part because they truly do have an unreliable *third-world* grid that they fully expect to fail routinely; and, in those places, civilization does not halt when the lights go out, as it seems to in advanced countries.

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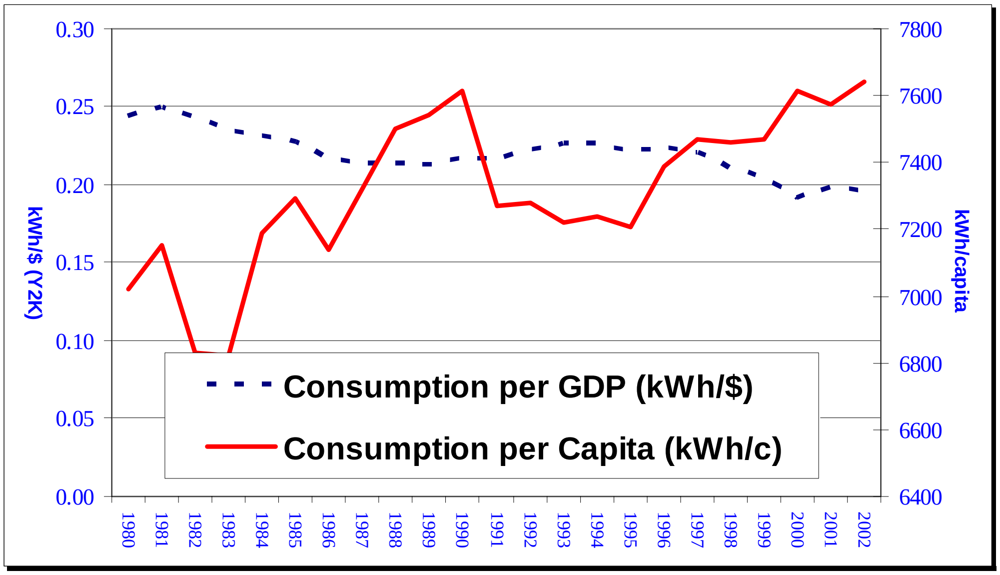
[1] Former Energy Secretary and sitting New Mexico Governor, Bill Richardson, was widely quoted making this claim.

Advanced power grids and advanced economies develop in parallel; as the grid becomes more reliable, other systems in the economy become less robust to grid weakness and failure. This interdependency is itself not troubling, and many mistakenly think it inevitable. The problem lies in that few efforts are typically made to specify economically efficient levels of electricity service, in stark contrast to many aspects of developed economies whose costs and benefits are subjected to intense analysis. A tacit assumption prevails that the grid can incrementally improve indefinitely such that our rising expectations for ever higher quality power can be affordably accommodated because, historically, on the whole, they have been. The vital questions not frequently asked are at what cost, for what benefit, and what are possible alternatives. A fundamental physical reason for this historic trajectory is the requirement that that interconnected power systems operate within tight tolerances, e.g. for system frequency. This requirement has tended to confuse engineering and economic standards. The standards for universal service should properly be established based on an evaluation of the inevitable societal trade-offs rather than on engineering rules of thumb and unrealistic expectations.

Limits to Expansion of the Grid

It appears unlikely grids can expand rapidly enough and perform well enough to meet the expanding needs of advanced economies, in large part because of expanding electricity consumption.

Figure 1. California Electricity Consumption Per Dollar of State GDP and Per Capita



source: California Energy Commission

California might be considered representative of highly developed and fairly diversified economies. Figure 1 shows the growth in California’s electricity consumption over the last two decades. Despite the improvement in the electricity efficiency of the economy, i.e. lower kWh usage per dollar of gross domestic product (GDP) created, per capita electricity usage continues to grow because of economic growth and technological change. Nationally, the latest Energy

Information Administration (EIA) forecasts foresee an increase in national electricity use of well over half during the first quarter of this century (EIA 2004). However optimistic predictions might be of energy efficient technology deployment, this growth trend is unlikely to reverse soon, and the added demand this will place on the national grid is potentially crippling. What makes the scenario much more troubling is that at the same time that our requirements of the grid grow more demanding, both in terms of the amount of energy that needs to be transported and the reliability and quality that needs to be maintained, the potential for enhancing the grid is becoming more limited. Investment in the U.S. grid has been in steady decline for a quarter century (DOE 2002). There are numerous possible explanations for this decay, but two of the ones commonly sited are: (1) the uncertainty of cost recovery that transmission owners face given the inconsistent pattern and pace of electricity supply industry restructuring, and (2) the increasing physical and political barriers to siting new transmission lines and equipment.

Alternatives to a Centralized Grid

Many authors have noted that power systems everywhere began as smaller isolated systems which, wherever possible, have been eventually interconnected and extended, often to eventually cover vast regions; in other words, distributed systems are closer to the roots of the power industry. While this is in a way correct, the march to larger interconnected systems began very early and was fully established soon after the turn of the last century, the triumph of AC over DC being in part driven by its amenability to high voltage long distance transmission of energy (Hughes 1983). Questioning of the inevitability of larger scales of generation and longer distances of transmission began when the benefits of large scale generation first showed evidence of decline in the late 1960’s and gained momentum with the nuclear fiascos of the 1970’s and 1980’s; however, serious analysis of the potential benefits of establishing a more decentralized system began only in the 1990’s. An extensive and rich literature has been accumulated since then. Innovative work done for and by the Pacific Gas and Electric Company first examined and attempted to quantify the benefits of distributed generation, and the general case for a smaller scale less centralized power grid. Iannucci et al provide an excellent summary and review of over 30 major contributions to this literature (Iannucci et al 2003). The general case for a decentralized power system has been laid out exhaustively by the Rocky Mountain Institute (Lovins et al 2002). More recently, Gumerman et al, proposed a simple framework for estimation of societal DER benefits (Gumerman et al 2003).

In addition to analysis of the implications of emerging smaller scale technologies, work is now emerging on the technical, organizational, and regulatory issues raised by the possible aggregation of small scale generators into localized groupings, or *microgrids*. The number of definitions of “microgrid” is roughly equivalent to the number of analysts working in this area, and no consensus seems likely soon.[2] But the general feature that seems to unite these concepts is that control of DER in a microgrid advances a step or two beyond the totally passive role that small-scale resources are currently assigned. In other words, most analysts consider a microgrid to be a grouping on some scale below the utility, usually within the service territory of a distribution utility, and yet operating to some extent outside its control.

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[2] Several microgrid concepts were presented at the California Energy Commission Staff Workshop to Explore Microgrids as a Distributed Energy Resource Alternative, held in Sacramento on 2 May 2002. Some of these and others are available at der.lbl.gov.

Development of the CERTS Microgrid Concept

The Consortium for Electric Reliability Technology Solutions (CERTS) is pioneering the concept of the CERTS Microgrid (CM) as an alternative approach for integrating small scale distributed energy resources (DER of < 500 kW) into electricity distribution systems, and the current wider power sector (the macrogrid) (Lasseter et al 2002). CERTS involves several participating institutions, but the ones most involved in CM development are the University of Wisconsin, Madison, Sandia National Laboratory, Georgia Institute of Technology, and Berkeley Lab. The viability of the CM has been shown in simulation and in bench tests. A laboratory test is planned for early 2005 to be followed by a field demonstration (Illinadala et al 2001; Illinadala et al 2004; Venkataramanan et al 2002). The CM does not fit into the traditional approach to on-site generation that focuses on minimizing the effect on safety and grid performance of a relatively small number of individually interconnected microgenerators, implying, for example, that they must instantaneously disconnect in the event of system outage. By contrast, the CM concept fits into the group of emerging microgrid concepts that envisages systems designed to operate semi-independently, usually operating connected to the macrogrid but separating (islanding) from it when cost effective or necessary.

The CERTS Microgrid Paradigm

A CM is a semiautonomous grouping of generating sources and end-use sinks that are placed and operated for the benefit of its members. The supply sources may include microturbines, fuel cells, photovoltaic systems (PV), and storage devices, all of which are interconnected through power electronic devices that could be enhanced to perform CM functions. Synchronous rotating generators are in a somewhat different class but could also be incorporated. Some end-use loads could also be controlled to permit efficient operation of the CM. For example, non-critical loads might be curtailed or shed during times of energy shortfall or high costs. While capable of operating independently of the macrogrid, the CM usually functions interconnected to the macrogrid, purchasing energy and ancillary services from the macrogrid as economic. The CM maintains energy balance through passive plug and play electronic interfaces that allow operation without tight central active control or fast communication, i.e. on time scales less than minutes. These interfaces permit connection and disconnection of devices without need for any reconfiguration of equipment, preexisting or new. Economic operation within constraints such as air quality permit restrictions, noise concerns, etc., as well as maintenance of a legitimate façade to the macrogrid is achieved entirely through slow communications.

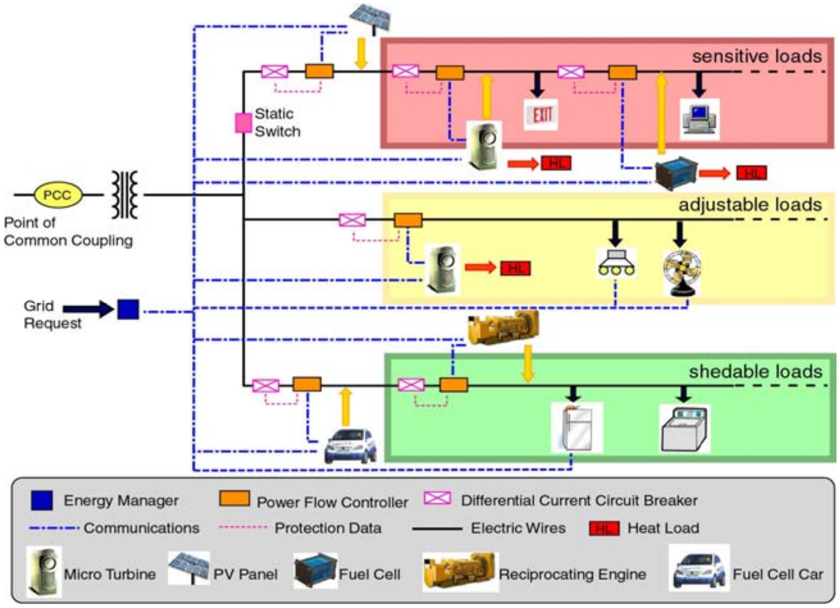
Two key features of the CM are its design around total system energy requirements and its provision of heterogeneous PQR to end-uses. Recovery of waste heat by combined heat and power devices represents a central design and operating principle. While small scale thermal generation of electricity is unlikely to be directly competitive with central station generation, the dramatically improved prospects for useful waste heat recovery, especially in absorption cooling systems, can tip the economic scales towards DER. The arrangement of a CM evolves from the need to optimize the overall energy system of the end-uses, and since transportation of heat is typically more limiting than transportation of electricity, the location of heat loads is likely to dominate. In other words, small scale generators may be distributed throughout sites to permit collocation with heat loads. A second central goal of the CM concerns tailoring PQR to the requirements of end-uses, a starkly different principle from the provision of universal service quality, which is the goal of macrogrids. The CM is built and operated so that critical loads are protected and high power quality is ensured where it is necessary, while other loads are served with PQR commensurate with their importance and/or reschedulability. The provision of heterogeneous PQR can improve overall reliability of critical equipment while lowering costs because of the sacrifice of non-critical ones. Provision of high PQR specific and local to end-uses will revolutionize thinking about the optimal level of universal PQR necessary in the macrogrid. Instead of striving for more macrogrid reliability, an economic level of reliability that captures the maximum possible benefit from openly traded central station power can be contemplated.

A critical feature of the CM is its presentation to the surrounding distribution grid as a single controlled system, akin to a current customer, or possible small generation source. Key to this characteristic is reliance on the flexibility of advanced power electronics that control the interface between microsources and their surrounding AC system. The CM architecture ensures that its electrical impact on the distribution grid is no different than other customers.

The CERTS Microgrid Paradigm

Figure 2 shows a schematic showing the key features of the CM.

Figure 2. Schematic of a CERTS Microgrid



It’s key features are:

(1) *single common coupling* -- The CM is interconnected to the macrogrid at a single point of common coupling, and from the outside it appears to the grid as no different from any other customer. In other words, although sophisticated control of devices exists within the CM, energy is not exported and its ability to island does not affect its performance while connected. Some other microgrid paradigms contemplate the possible export of energy and the provision of local ancillary services, such as VAR support. The CM is in principle capable of operating in this way,

but in the short-term, it is seen as operating within the traditional regulatory and technical framework as much as possible, and this is achieved by its appearance as a customer, i.e. as a net buyer at all times.

(2) *generator control by on-board power electronics* -- Close to each device in the figure are devices described as a power flow controller and a differential current circuit breaker. These represent the extended capabilities of the on board power electronics that comes with most of the devices shown, i.e. PV, microturbine, fuel cell, fuel cell powered vehicle. The reciprocating engine shown is a synchronous device, and work is underway to solve the technical problems of connecting synchronous generators to the CM. Each device operates without fast electrical control. Based on local frequency and voltage readings, the on-board power electronics of each device enables secure operation of the CM that maintains the energy balance. Operations must take place in two distinct modes, connected to the grid and disconnected. In the former case, transients, e.g. start up currents, can be covered by the grid, but in the later, the CM must function fully independently.

(3) *slow supervisory control* -- Although the devices operate without fast electrical control, i.e. on time scales of cycles, they clearly need slower operational control to ensure economic commitment and dispatch within environmental and other constraints, represented in Figure 2 by the Energy Manager (EM). The EM is conceptual and could be realized in many forms, e.g. through the extension of an existing building energy management and control system (EMCS) to add DER control capability. The *grid request* label is intended to suggest that the CM might be buying electricity and/or fuels at spot prices, participating in demand response programs, or receiving other real-time information, e.g. weather data. The complexity of the EM might cover a broad range, and some control issues, such as ones related to the uncertainty of price spikes and/or demand charges, could be truly daunting (Kueck 2002, and Firestone et al 2004).

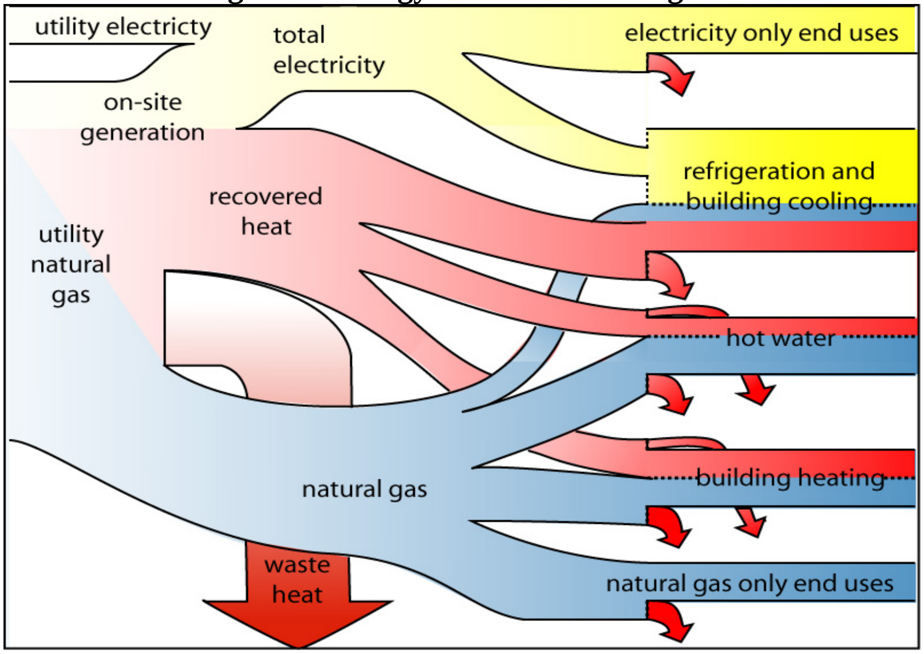
(4) *CHP applications* -- Note the placement of devices within the CM. The thermal generators are placed where the heat loads permit useful application of the waste heat. While the economic value of waste heat, especially in moderate climates such as California, is typically small relative to the value of electricity, it can nonetheless have a major impact on CM economics. When applied in absorption cooling systems, however, the heat can be quite valuable. Cooling by use of indirect heat not only potentially displaces expensive on-peak power, it can also have a significant effect on demand charges, which tend to operate like an extreme form of peak pricing. Displacing cooling loads also lowers the optimum generation and other system capacity, yielding still more economic benefits.

(5) *heterogeneous PQR* -- Finally, consider the concept of heterogeneous PQR. The ideal of our current power system paradigm is that PQR meets a universal standard. While in practice this ideal is not always met, the ideal nonetheless holds. In the diagram, the loads are segregated onto three separate circuits. The end-use loads that must be met if at all possible are deemed *sensitive loads*. If energy balance within the CM cannot be maintained, this circuit would isolate itself at the static switch and would operate independently. The *adjustable loads* are on a second circuit, and the loads that would be abandoned first are on a third *shedable loads* circuit.

Microgrid Design

Figure 3 shows the energy flows within a microgrid. On the left side are energy inflows; in California, these are typically utility electricity and natural gas. On the right side are the useful energy flows. Here they are segregated into five categories. Some loads can be met only by electricity, e.g. lighting or computing, and some can be met only by direct natural gas firing, e.g. cooking. Some can be met by either waste heat or direct fire, most notably space heating and domestic hot water production. Finally, the cooling and refrigeration loads are in a special category because they can be served by traditional compressor cooling, by direct gas-fired absorption cooling, or by indirect waste heat driven absorption cooling. The key to optimizing microgrid performance is to pick equipment that optimally buys, applies, and converts the energy inflows on the left into the useful energy flows that serve energy needs on the right side. In detail, this can be a highly complex problem, but at a superficial level, it can be solved analytically, as the Distributed Energy Resources Customer Adoption Model (DER-CAM) (described below) does (Bailey et al 2003).

Figure 3. Energy Flows in a Microgrid



Analysis of A Potential Microgrid

Description of Site

Naval Base Ventura County (NBVC) is comprised of two nearby bases located 100 km northwest of Los Angeles, Naval Air Reserve Point Mugu and Port Hueneme. Building 1512 at Port Hueneme is approximately 13,000 m^2 and the largest electricity consumer at either base. Building 1512 is comprised of a Navy Exchange, (NEX), a large retail store, and the Commissary, which is a large grocery store, along with other smaller stores and a food court.

The base holds a legacy direct access electricity contract with an energy service provider, Strategic Energy, and electricity delivery is through Southern California Edison (SCE). The base Public Works Department internally recharges Building 1512 a standard flat rate of $13.49/MWh for electricity and $7.92 x 10^{-3} MJ ($7.51/MBTU) for natural gas.

Analysis

The Distributed Energy Resource Customer Adoption Model (DER-CAM) is a tool designed to find the optimal combination of installed equipment and an idealized operating schedule that would minimize the site's energy bills, given performance and cost data on available DER technologies, utility tariffs, and site electrical and thermal loads over an historic test period.

Hourly electric and thermal energy data are developed in DOE2 for each of five loads used to model the building: electric-only loads, space heating, space cooling, water heating, and natural-gas-only loads. These loads are then scaled to match available utility bill data that consisted of monthly electric and gas meter readings (only kWh readings available).

The assumptions used are: (1) loads modeled over one year and assumed accurate and consistent over the 20-year lifetime of DER technologies; (2) electricity and gas tariffs assumed to be constant over the lifetime of DER equipment; (3) 5% interest rate compounded annually charged on investment expenditures; (4) 80% efficiency of conversion of natural gas to serve space heating and water heating loads and also an 80% efficiency of converting residual CHP heat to loads; (5) coefficient of performance of electric chillers 5, and 0.65 for absorption cooling; (6) consistent DER technology installed costs and performance specifications taken from one source wherever possible (NREL 2004).

Results

Building 1512 is the largest electricity consumer on NBVC, and, not surprisingly, the results show that the benefits of DER at Building 1512 are highly dependent on the electricity tariff used in the analysis. At a certain point, on-site power generation would switch the building's energy consumption from almost all electricity (as it is now) to almost all natural gas. At current direct access contract rates, which average about 8.5 ¢/kWh, and given assumptions about the performance and structure of building energy loads and available generating technologies, DER-CAM results indicate that a cost minimizing DER installation would deliver negligible savings of about 1% of the $487,000/year bill. Nonetheless, DER-CAM finds the optimal system is installation of a 1 MW natural gas engine with absorption cooling that would fully meet the site's electricity requirement. The low savings are due primarily to two factors: the low electricity rates the base receives through a direct access energy service provider, and inability to utilize residual heat from DER technologies. This latter stems in part from the lack of heat loads in the building and the inability of the current version of Distributed Energy Resource Customer Adoption Model (DER-CAM) to analyze use of residual heat used for refrigerator and freezer cooling applications.

If electricity rates increase, either due to the change in commodity prices available through the direct access provider or because the contract is not renewed, then DER could be cost effective at Building 1512 at the base. A rate structure or commodity price change could easily raise the annual energy bill by $50,000 or more annually. If on the default SCE rate of about 9.6 ¢/kWh it could otherwise face, absent the Navy contract, a similar DER system would deliver about 8% bill savings. Currently, the decision to install DER would have to be driven by other factors such as reliability or the ability to delay on base distribution infrastructure investments. Public Works staff and Building 1512 managers may want to explore the option of putting some of the building loads on critical load circuits backed up by a DER system, although the base is a non-curtailable customer. Another option to consider is combining other buildings with heat loads near Building 1512 into a microgrid, possibly including the swimming pool and a laundromat, which would provide more potential heat sinks.

Conclusion

The blackouts of summer 2003 underscored the dependence of western economies on reliable supply of electricity with tight tolerances of quality. While demand for electricity continues to grow, expansion of the traditional electricity supply system is constrained and is unlikely to keep pace with the growing appetite western economies have for gourmet electricity. Furthermore, no compelling case has been made that continual improvement in overall PQR delivered is possible and desirable. An alternative path to providing for sensitive loads is to site generation close to them. This would alleviate the pressure for perpetual improvement in grid PQR, and might allow the establishment of sounder economically based level of universal service, which may be better or worse than we have today.

Providing for loads by means of local power generation is becoming increasingly competitive with central station generation for a number of reasons, four key ones being non-technical constraints on expansion of the grid, improvements in small scale technologies, opportunities for CHP application, and the ubiquitous nature of sensitive loads in advanced economies. Along with these new technologies, concepts for operating them partially under local control in microgrids are emerging. The CM is one form of microgrid that is being developed. It has been demonstrated in simulation, and a laboratory test of a three microturbine system is planned for late 2004 and early 2005.

Acknowledgements

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Glossary

AC/DC	alternating/direct current
Berkeley Lab	Ernest Orlando Lawrence Berkeley National Laboratory (http://www.lbl.gov)
CERTS	Consortium for Electric Reliability Technology Solutions (http://certs.lbl.gov)
CHP	combined heat and power, also called cogeneration
CM	CERTS Microgrid
DER	distributed energy resources
DER-CAM	DER Customer Adoption Model
DOE	U.S. Department of Energy (http://www.energy.gov/)

EIA	Energy Information Administration (http://www.eia.doe.gov/)
EM	Energy Manager, slow control of the CM
EMCS	energy management and control system
MISO	Mid-West Independent System Operator
NEX	Naval Exchange (big box store for Navy personnel)
NREL	National Renewable Energy Laboratory (http://www.nrel.gov/)
NVBC	Naval Base Ventura County
PQR	power quality and reliability
PV	photovoltaics
SCE	Southern California Edison Company

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