LBNL-63520

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Microgrids for Commercial Building Combined Heat and Power and Power and Heterogeneous Power Quality and Reliability

Chris Marnay[a], Ryan M. Firestone[a], Judy Lai[a], and Giri Venkataramanan[b]

[a]*Environmental Energy Technologies Division, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley 94720, USA*
[b]*University of Wisconsin, Madison, WI 53706, USA*

Environmental Energy
Technologies Division

October 2007

http://eetd.lbl.gov/EA/EMP/emp-pubs.html

The work described in this report was funded by the Office of Electricity Delivery and Energy Reliability, Distributed Energy Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Disclaimer

paper to be presented at the *IEEC 2007 Conference on Active Networks and Sustainable Energy Consumption*, Bilbao, Spain 14-15 Nov 2007

MICROGRIDS FOR COMMERCIAL BUILDING COMBINED HEAT AND POWER AND HETEROGENEOUS POWER QUALITY AND RELIABILITY

Chris Marnay, Ryan Firestone, & Judy Lai
Ernest Orlando Lawrence Berkeley National Lab.
1 Cyclotron Rd MS 90R4000
BERKELEY CA 947208136
U.S.A.

Giri Venkataramanan
Univeristy of Wisconsin, Madison
1415 Engineering Drive
MADISON, WI 53706
U.S.A.

ABSTRACT

Electricity supply may be entering a period of significant change, and currently there are conflicting visions for the reshaped industry. A major share of the uncertainty revolves around the pressing need for carbon emissions abatement, while at the same time, there is an additional and growing requirement of modern economies for high power quality and reliability (PQR). The developed economies must urgently find the most cost effective means of meeting these two objectives. This paper begins by describing two stylized alternative visions in popular currency of how the power system might evolve to meet increasing future requirements for PQR, a *supergrids* paradigm and a *dispersed* paradigm. An economic perspective is presented on the choice of homogeneous universal power quality upstream in the electricity supply chain, and on the extremely heterogeneous requirements of end-use loads. One promising approach discussed for addressing our current challenges is via the deployment of *microgrids* in commercial buildings. The *Distributed Energy Resources Customer Adoption Model* (DER-CAM), an optimization approach to choosing such systems and their operating schedules, is described and recently added extensions to incorporate heat and electrical storage options are demonstrated. An illustrative example for a San Francisco hotel is reported.

1. INTRODUCTION

Rapid (if not accelerating) technological change surrounds us, and the nature of the electricity suppy system will inevitably evolve over time. Our current centralized paradigm is potentially entering a period of significant fundamental change of a kind not seen for a century, and conflicting visions exist regarding the form the reshaped industry may take. A major share of the uncertainty revolves around the pressing need for carbon emissions abatement, while there is an additional and growing requirement of modern economies for high quality electrical service. The developed economies must urgently find the most cost effective way to meet these two objectives. Because commercial and residential energy consumption tend to dominate energy use (especially electricity use) in postindustrial economies, and because recovering the energy lost in conversion from primary sources to electricity offers one of major potential carbon reduction gains, the viability of combined heat and power (CHP) applications in buildings is of particular interest. Simultaneously, the choice of homogeneous universal power quality upstream in the electricity supply chain and the efficient provision of power quality and reliability (PQR) matched to extremely heterogeneous requirements of end-use loads pose additional challenges.

Consumption of electricity continues to grow in developed economies. For example, U.S. consumption of electricity is forecast to increase roughly by half over the current quarter century [1]. Most analysts anticipate a role for *dispersed resources* in the much expanded generation capacity that will be required to meet this seemingly inexorably expanding demand. Herein, dispersed resources are considered to be generation with capacities too small to directly participate in wholesale markets, e.g. $\approx<1$ MW, such as small-scale combined heat and power (CHP) installations (possibly burning biofuels), photovoltaics (PV), fuel cells, local heat and electricity storage, etc. Trends emerging in the power system suggest that the centralized paradigm that has dominated power systems for the last century may eventually be replaced, or at least diluted, by an alternative one in which control is more dispersed, and universal quality of service is replaced by heterogeneous service tailored to the requirements of classes of end-uses. The dominant theme of current thinking about the development of such dispersed sources is in terms of the value it can provide to its owner and to the wider existing power system, and the technical challenge of integrating it into the current power system. But the existence of dispersed energy sources and controlled sinks, possibly grouped in *microgrid*, that exercise some autonomy may ultimately change the nature of the familiar grid itself more fundamentally. Currently, development of microgrid technology is an active area of research in several countries [2].

2. POWER QUALITY AND RELIABILITY

Our current dominant paradigm consists of large-scale central station generation, long distance bulk transmission of energy over centrally operated high voltage meshed grids, and local distribution at ever lower voltages through simpler, partially-locally-managed, unidirectional, radial lines. A key feature of this structure is that universal service power is, in principle, delivered at a consistent level of PQR throughout large regions. For example, PQR targets are consistent virtually all across North America, and where standards cannot be met, it is usually the result of a local technical difficulty and not the outcome of a deliberate attempt to deviate from the universal norm. This predictability of service delivers an enormous economic benefit because all types of electrical equipment can be built to meet a homogeneous universal standard. Indeed, the traditional paradigm has served developed economies well for a very long period, during which the uses for and consumption of electricity have increased enormously, even at times spectacularly. As is often observed, modern life as we currently experience it seems impossible without such ubiquitous, universal, reliable, high quality power. To be clear, higher PQR is unequivocally better than lower, i.e. it is an economic good. Changes in expectations for our power supply system on both the supply and demand sides are bringing us to a turning point in its evolution and quite possibly to the first paradigm shift in over a century. Improving traditional universal service to the point at which it can meet the requirements of sensitive loads may be unnecessarily costly. The changes on the demand-side result from our seemingly unquenchable thirst for electricity in an emerging digital age that is significantly tightening our PQR requirements for some applications. On the supply-side, our ability to maintain current standards are being brought into doubt by concerns about terrorism, restrictions on system expansion, the uncertainties of volatile markets in energy short times, and (most importantly from a carbon abatement standpoint) integration of high penetrations of intermittent renewables [3].

3. ALTERNATIVE VISIONS

The schematics in Figs. 1 and 2 below show two alternative visions in current currency of how the power system might be retooled to provide high PQR, *supergrids* and *dispersed* paradigms. These are only two stylized representations of many possible paths, and full justice cannot be given here to the technical intricacies of any specific vision. The intent is only to contrast in a comprehensible way the central theme of multiple divergent alternatives. For more detail on a supergrids leaning view, see Gellings *et al*, Amin, or Lee [4,5,6]. A comprehensible vision for a dispersed grid is presented by the European Commission, or, for other voices from the dispersed camp, see Lasseter, or Marnay and Venkataramanan, but these are by no means the only contributors to this ongoing debate [7,8,9].

The x-axis in both figures roughly covers the historic development of the existing power supply system, while the y-axis in both figures simply shows availability in nines together with the equivalent annual expected outage duration. Other dimensions of PQR are harder to portray so they do not appear explicitly, but somewhat more abstractly, similar arguments can also be made with respect to them. Typical U.S. electricity service today is in the 3-4 nines range or a few hours of expected annual outage, which is poor performance relative to most developed countries. As the large grids curve shows, over the last century, improved technology and interconnection over larger areas have steadily improved reliability. Nonetheless, in the U.S. case, following the northeast blackouts of the 1960s and 1970s, the need to provide local backup sources for critical loads was recognized and introduced into building codes and other regulations. A formal dispersed electricity supply system shown by the solid dispersed resources curve was thereby established, primarily in the form of the now ubiquitous diesel backup generator.

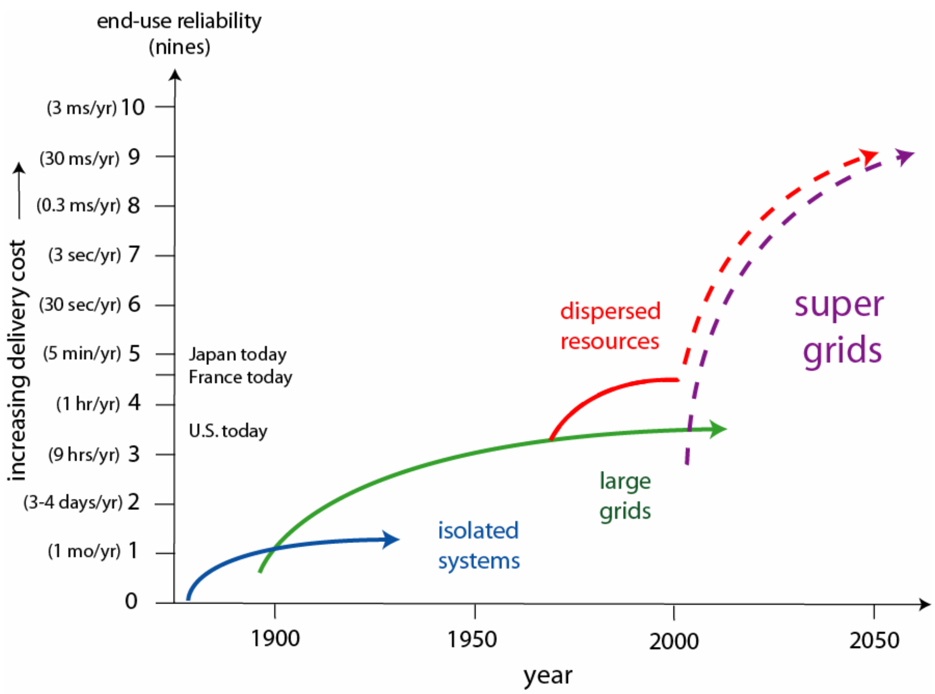

Figure 1. *Supergrid Paradigm.*

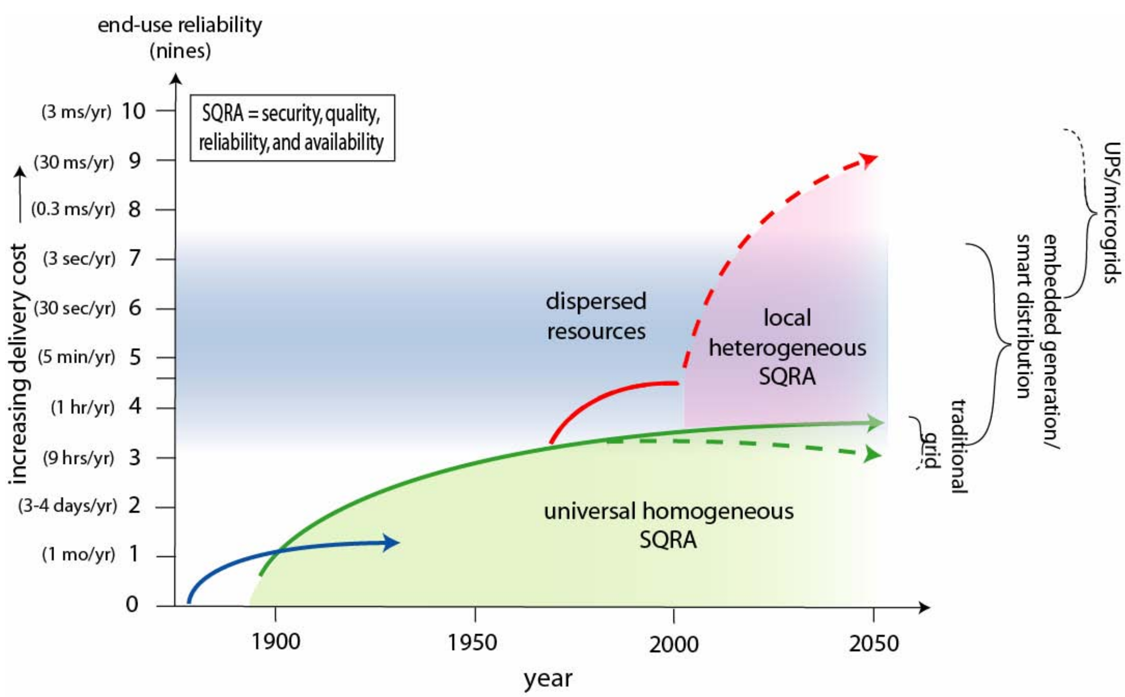

Figure 2. *Dispersed Grid Paradigm.*

3.1. Supergrids Paradigm

The steady rise of sensitive loads over more recent times has led to widespread additional use of backup generators, uninterruptible power supplies, and other equipment to ensure high quality energy supply to such loads. Protecting them from service that deviates from standards is at the heart of the divergence in visions. The supergrids camp holds that deployment of diverse suites of new technologies can significantly improve the performance of all elements of the power supply chain built around the traditional paradigm, as shown in Fig. 1 by the lower dashed line. Despite the goal of across-the-board technical improvement, much of the improvement inevitably must come in the distribution system because most outages occur there, over 90% in the case of the U.S. It forms the most vulnerable link because of its sheer size and dispersion, as well as its exposure to the myriad hazards of extreme weather, accidents, and mischief. Even in the supergrids view, inevitably there will be end-uses that require PQR beyond even the performance of the much enhanced delivery chain, but these can be kept to a minimum.

3.2. Dispersed Paradigm

Fig. 2 shows an example schematic of a dispersed vision whose key salient feature is increased reliance upon (rather than minimization of) dispersed resources. In this view, traditional universal grid service is not improved significantly but rather possibly holds steady at current levels. Sensitive loads are then increasingly served locally in two ways: first, improvements in the distribution system (as in the supergrids vision) are deployed to improve on the existing system's weakest link; and second, widespread use of supply and other resources close to sensitive end-uses protect them at the levels they demand. Finally and most heretically, some deterioration of universal PQR is possible in this paradigm, as the lower dashed traditional grid line shows.

3.3. Paradigm Comparison

A number of key differences between the two paradigms should be noted.

1. In the dispersed vision, the performance of generation and high voltage transmission is not called upon to achieve significant improvements, although conversely they are not precluded. The level of bulk power PQR is determined somewhat independently of end-use requirements based on technical, economic, and security realities.
2. To some extent they both depend not only on better distribution technology *per se*, but also on the existence of local generation embedded in the distribution system that permits the provision of reliable service somewhat independently of the upstream power system. In this regard, the difference between the two paradigms is simply a matter of degree.
3. In the dispersed paradigm, local to actual end-use loads, a wide range of additional technologies is employed to ensure adequate service to loads requiring higher-than-universal-level PQR. In some cases, this equipment may be clustered in electronics based microgrids.
4. This dispersed paradigm represents a major break with tradition in the sense that PQR of electricity arriving at customer meters might vary with local conditions, and the PQR at end-use devices varies even more so, based on local requirements. This aspect can be thought of, as is shown in the diagram, as delivered electricity being of the familiar universal homogenous PQR upstream, but increasingly heterogeneous downstream, depending on the sensitivity or value added of various end-uses. Further, the shaded area in the figure is intended to show that levels of PQR delivered and how they are achieved are far from resolved, and no definitive dividing line between sources is apparent.
5. It should be noted that in the dispersed paradigm, the optimal level of PQR could potentially be even lower than current standards, as shown by the declining dashed traditional grid line, whereas in the supergrids paradigm, all links in the supply chain must improve.

The notion of heterogeneous PQR (HeQ) exists to some extent in both visions described above, but is central to the dispersed vision. The essence of the supergrids paradigm is homogeneous PQR (HoQ). In principle, near perfect electricity is delivered everywhere in the system at all times; nonetheless, HeQ creeps in because the expensive investments necessary to improve PQR are unlikely to be made universally and evenly across the system. These limitations notwithstanding, the objective of the supergrids vision is an extension of the current paradigm in which HoQ is dramatically improved.

In the dispersed vision, as shown in Fig. 2, PQR diverges from the standard downstream of the substation. Safe and economic operation of the high voltage meshed grid relies as it always has on tight standards and centralized operation; however, downstream, PQR becomes increasingly heterogenous, with delivered electricity to the end-use potentially diverging considerably. Two obvious questions arise: 1. Given that locally, HeQ is tailored to end-use loads and can deviate in either direction from the upstream HoQ, how should the standard for upstream HoQ be chosen? And

2., why does HeQ make sense at the end-use level? The following two sections address these two questions.

4. CHOOSING THE HoQ STANDARD

As explained above, while the ideal is rarely achieved in practice, the prevailing current paradigm is to universally provide HoQ to every load in the network at all times. In the dispersed vision this remains true only upstream in the grid, and the question at hand is how should this upstream level of HoQ be chosen.

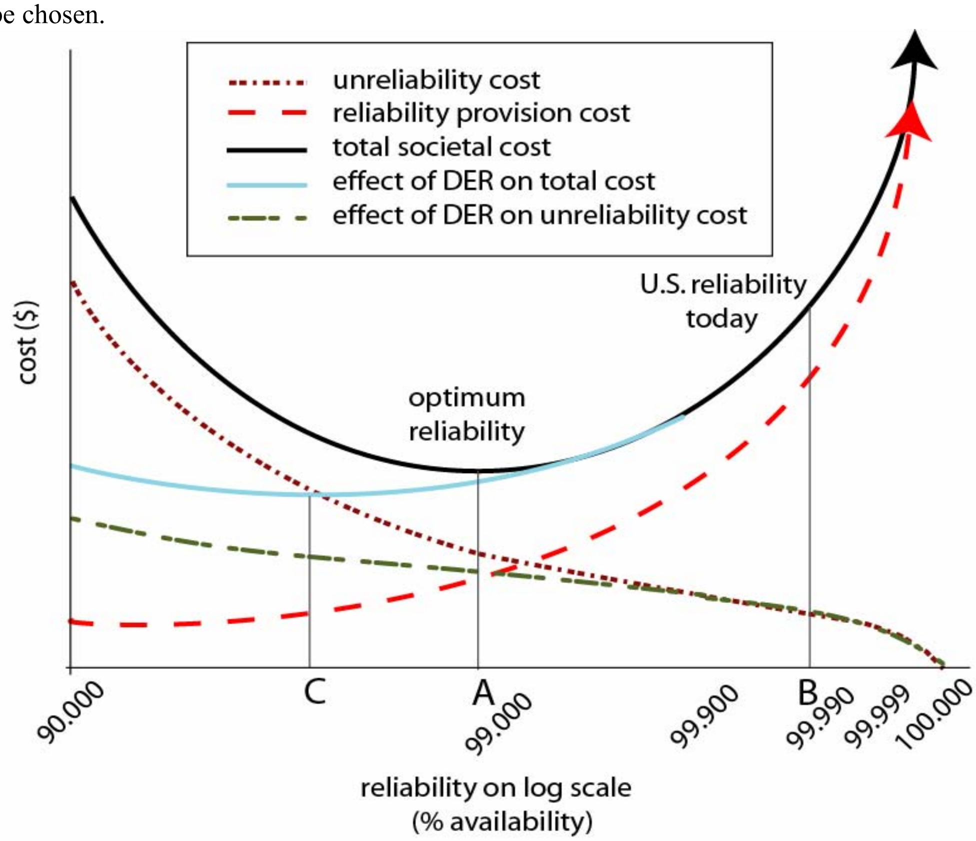

***Figure 3**. Finding Optimal HoQ.*

The x-axis of Fig. 3, like the y-axes of Figs. 1 and 2, shows some measure of PQR, represented in this case as availability. The y-axis shows the societal cost of providing PQR. This cost has two components, the cost of providing reliability and the cost of the residual unreliability, with the sum of the two representing the total societal cost. The dotted unreliability cost curve shows what we all know well; namely, that poor PQR costs the economy dearly. These costs might be high to the left, where many developing countries find themselves, and would fall to zero on the right, if perfection could be achieved. The dashed reliability provision cost curve shows the cost of providing PQR. Better service incurs higher costs of two types, the equipment costs of a physically more robust system and the foregone electricity trade prevented by conservative grid operations imposed for reliability reasons. While the relative magnitudes of the two cost components are unclear, the latter may well be the larger. The nature of the curves in Fig. 3 is purely conceptual and no comprehensive data are available to construct such curves.

The solid total societal cost curve simply represents the sum of the two curves, the cost consequences of having an imperfect system plus the out-of-pocket cost of providing the prevailing level of PQR. The societal optimum is clearly at the point of minimum total social cost, point A, which in Fig. 3 occurs to the left of the current U.S. target of about 3-4 nines, point B, and even further to the left of Japan's. The dispersed paradigm would tend to have the effect of lowering the unreliability cost because loads that require high PQR are provided for locally, making systems more resilient. It is pure speculation at this point what the net effect would be, but one credible possibility is that the societal optimal could be pulled leftwards, to a point such as C.

5. END-USE HeQ

Various indices for measuring PQR are often used in quantifying levels of electrical service [10]. While technical analysis of electricity service PQR can be sophisticated, by contrast, analysis of the economics of the PQR is at best rudimentary, which makes it difficult to relate its importance to the energy side of power systems. In other words, it tends to be quite easy to measure the energy value of electricity but hard to measure its PQR value, and consequently rather little can be said abut the correct level of PQR for any given end-use. Nonetheless. t is intuitively appealing to think that delivering PQR tailored to the requirements of end uses, as is the case in the dispersed paradigm, can generate higher economic benefits than universal PQR that never quite matches the requirements.

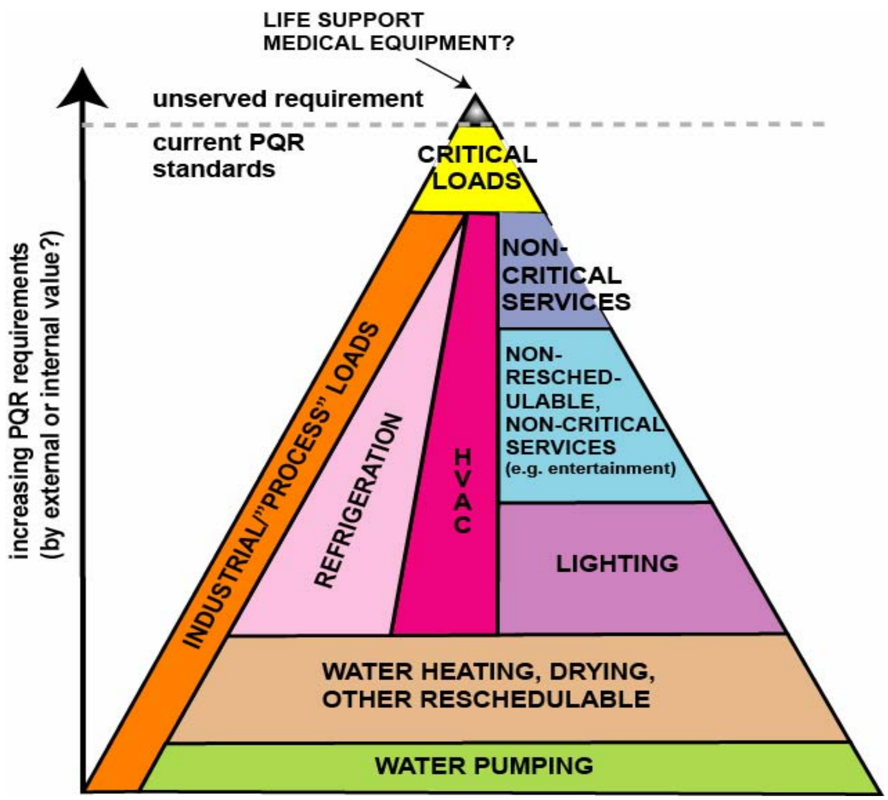

***Figure 4**. An HeQ Pyramid.*

Consider the pyramid shown in Fig 4, which illustrates how various electricity uses might be classified according to their PQR requirements. Some common loads, such as pumping, are widely agreed to have low PQR requirements and appear at the bottom of the pyramid, and vice-versa. Other loads can be much harder to classify; e.g., refrigeration is reschedulable in many applications, but might be critical in others, such as medication storage. At the top of the pyramid, the exposed peak above current standards shows that not all requirements are currently met. The layout of end-uses is highly speculative and simply intended to show how HeQ might be considered. More important is the pyramid shape itself. It is clearly not a natural law that low PQR demanding loads vastly outnumber critical ones, but if we behave economically, we would attempt to make them so. In other words, serving the low requirements loads at the bottom is cheap, and vice-versa for the sensitive loads at the top. We should be trying, therefore, to classify as much of the overall load in the base as possible.

6. DER IN BUILDINGS

The importance of the commercial sector in electricity consumption in developed countries can be seen by three multiplicative factors. 1. The share of all energy being consumed as electricity increases, e.g. in the U.S. from 13% in 1980 to about 20% today. 2. The commercial sector uses a growing share of all electricity, e.g. in the U.S. from 27% in 1990 to 35% in 2005. And 3., typically an increasing share of electricity is generated thermally as carbon-free hydro sources are fully exhausted, although the shares of carbon-free nuclear vary widely across grids. The product of these factors means the carbon footprint of commercial buildings can grow rapidly, but changes in the fuel mix, e.g. more natural gas fired generation, can also have a big effect. Further, in warm climates such as most of the U.S. and Japan, and for an increasing share of Europe, commercial sector cooling is a key driver of peak load growth, and hence the stress to and investment in the macrogrid. Consequently, deployment of DER in buildings, especially CHP technologies for cooling, is central to containing the growth of electricity consumption and its associated carbon emissions.

Yet despite the importance of DER in the commercial sector, current analysis of DER implementation in buildings is limited. System sizing often relies on heuristic rules based on the relative size of heat and electricity requirements. Further, the detailed building energy modeling that is frequently done during building design to assist in the selection of energy systems relies on quite limited programs

7. DER CUSTOMER ADOPTION MODEL (DER-CAM)

DER-CAM solves the commercial building DER investment optimization problem given a building's end-use energy loads, energy tariff structures and fuel prices, and an arbitrary list of equipment investment options [11]. Fig. 5 shows the energy flows in a building, from incoming commercial energy on the left to useful end-use energy flows on the right. Other opportunistic fuels might also be attractive, and the Sankey shows both solar thermal and solar PV inflows. DER-CAM picks the equipment for generation, storage, and end-use that minimizes total annual cost. The approach is fully technology-neutral and can include energy purchases, onsite conversion, both electrical and thermal onsite renewable harvesting, and end-use efficiency investments. Further, system choice considers the simultaneity of the building cooling problem; that is, results reflect the benefit of displacement of electricity demand by heat activated cooling that lowers building peak load and therefore the generation requirement. Regulatory, engineering, and investment constraints are all considered. Energy costs are calculated using a detailed representation of utility tariff structures and fuel prices, as well as amortized DER investment costs, and operating and maintenance (O&M) expenditures. For a specific site, the source of end-use energy load estimates is typically building energy simulation using a model based on the DOE-2 engine, such as eQUEST, or the more advanced but less user-friendly EnergyPlus [12,13].

The output from DER-CAM is a cost minimizing equipment combination for the building, including CHP equipment and renewable sources. The model chooses the optimal combination, fully taking the simultaneity of choices into account. The results of DER-CAM suggest not only an optimal (potentially mixed technology) microgrid, but also an optimal operating schedule that can serve as the basis for a microgrid control strategy; however, the rigors of optimization necessitate simplification of many real-world engineering constraints that would in practice necessarily be addressed through more detailed engineering analysis and system design.

Optimal combinations of equipment involving PV, thermal generation with heat recovery, thermal heat collection, and heat activated cooling can be identified in a way that would be intractable by trial-and-error enumeration of possible combinations. The economics of storage are particularly complex, both because they require optimization across multiple time steps and because of the influence of tariff structures. Note that facilities with onsite generation will incur electricity bills more biased toward demand (peak power) charges, and less toward energy charges, making the timing and control of chargeable peaks of particular operational importance. Similarly, if incentive tariffs that share the macrogrid benefits of DER with the microgrid are available, the operational problem is further complicated because identifying any potential contribution to the macrogrid would likely be intractable without optimizing algorithms.

This paper reports results using recently added electrical storage capabilities, both electrical and thermal storage being viewed as inventories At each hour, energy can either be added (up to the maximum capacity) or withdrawn (down to a minimum capacity to avoid damaging deep discharge).

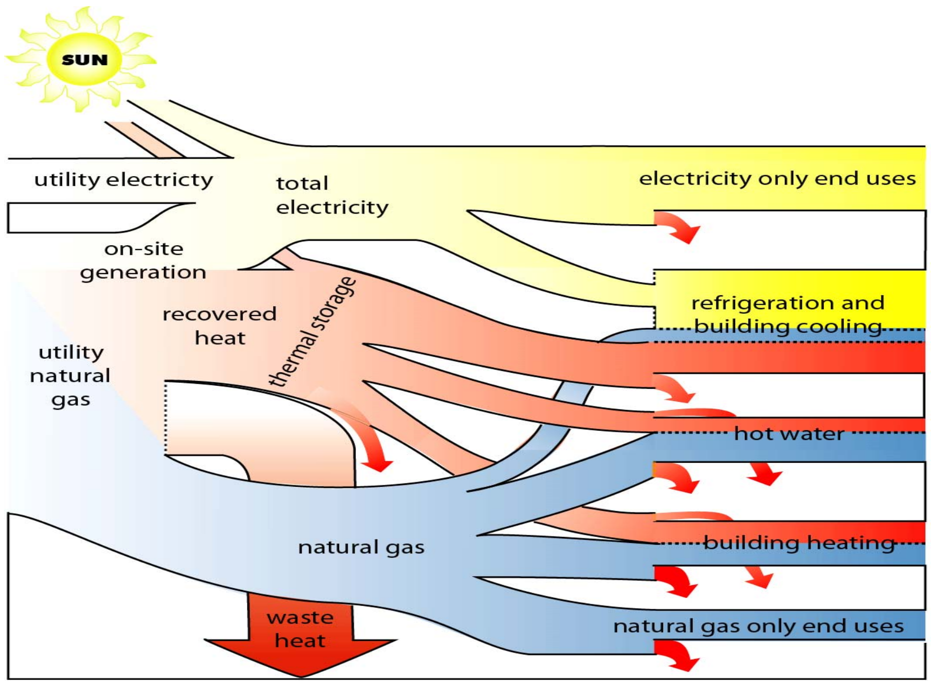

Figure 5. *Sankey Diagram of Building Energy Flows.*

8. SAN FRANCISCO HOTEL EXAMPLE

An example analysis was completed of a prototypical San Francisco, California, hotel operating in 2004. This hypothetical facility has 23 000 m^2 of floorspace and a peak electrical load of 690 kW. The electricity prices used, which are local Pacific Gas and Electric (PG&E) rates, were obtained from the Tariff Analysis Projects database [14]. Natural gas prices for the region were obtained from the Energy Information Administration web site [15]. A marginal carbon emission factor of 140 g/kWh for electricity purchased from PG&E was assumed, based on Price, *et al* [16].

Technology options in DER-CAM are categorized as either discretely or continuously sized. This distinction is important to the economics of DER because equipment becomes more expensive in small sizes. Discretely sized technologies are those which would be available to customers only in a limited number of discrete sizes and DER-CAM must choose an integer number of units, e.g. microturbines. Continuously sized technologies are available in such a large variety of sizes that it can be assumed capacity close to the optimal could be acquired, e.g. battery storage. The installation cost functions for these technologies are assumed to consist of an unavoidable cost (intercept) independent of installed capacity ($), plus a cost proportional to capacity ($/kWh).

9. RESULTS

The optimal system consists of two gas engines and an absorption chiller with no storage. Relative to a *do-nothing* case, i.e. depend on all conventional commercial energy and equipment, the expected annual savings for the optimal DER system are $53 000/a (11.5%) and the elemental carbon emissions reduction is 59 t/a (10.4%). A run was executed to demonstrate storage capability a low storage price case, both avoidable electrical and thermal storage costs are set to zero plus an avoidable $40/kWh cost. A more complex DER system results in which some generation capacity is replaced by storage and solar thermal collection, but the annual costs are reduced by less than one additional percentage point. In other words, the added value of the storage and other complexity is very modest in this example.

Note that these results are estimated assuming perfect reliability of DER equipment. Imperfect reliability would mostly directly affect the demand charges, but would also have other effects on the value of the project to the site. The graphics in Figs. 6 and 7 show DER-CAM operating results from the low storage price case for the thermal and electrical balances of the hotel on a typical July day in 2004. Note that the optimal technologies are a 200 kW reciprocating engine, a 585 kW (166 U.S. refrigeration tons) absorption chiller, 722 kW of solar thermal collectors, 1100 kWh of electrical storage, and 299 kWh of thermal storage. While the economics of this case are not compelling, even with subsidized storage, it is presented in detail to demonstrate the scheduling capability of DER-CAM.

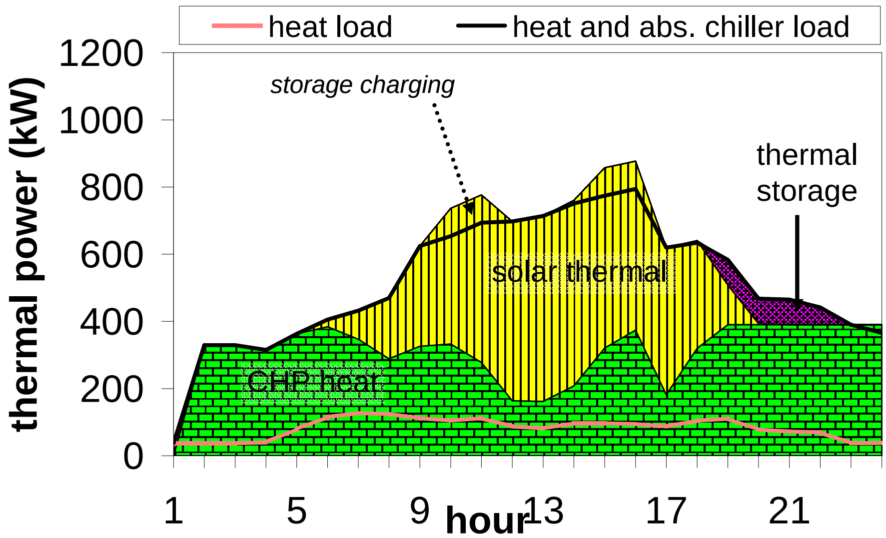

Figure 6. *Low Storage Price Diurnal Heat Pattern for a July Day.*

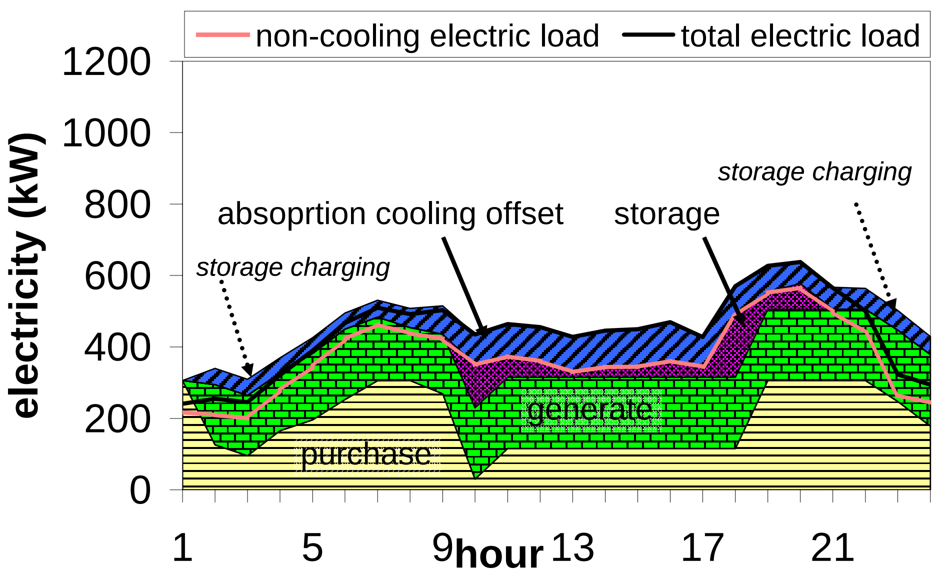

Figure 7. *Low Storage Price Diurnal Electricity Pattern for a July Day.*

The area underneath the solid black line in these figures is the hourly energy demand. Area above the solid black line indicates storage charging. The various patterns in the graphs indicate the source of the energy. For thermal loads, in Fig. 1 the lower line indicates the heat required for heating, whereas the solid black line indicates the total thermal load, including heat required for the absorption chiller. For electricity loads, Fig. 7, the lower profile indicates the portion of the electric load that can be met by only electricity, whereas the solid line above it is the total electric load, including cooling. Note that electric cooling loads can be offset by the absorption chiller.

10. CONCLUSIONS

Limiting the growth of electricity consumption in commercial buildings is particularly important for carbon abatement in developed countries, and at the same time, the increasing requirements for high PQR might be effectively met by semi-autonomous microgrids. Unfortunately, the promising approach of deploying CHP (especially cooling) technology faces major challenges. Use of better building energy analysis and design tools can accelerate the adoption of CHP, and thereby facilitate deployment of microgrids that can additionally deliver PQR benefits. Both thermal and electrical storage capability have been added to DER-CAM, making it a more useful optimization tool for onsite generation selection and operation. The new capabilities have been demonstrated by an analysis of a prototypical San Francisco hotel. It should be noted that although the example demonstrated herein has primarily focused on the optimal choice of investments, optimization of runtime operational schedules are implicit in the method, and examples are reported as figures.

11. REFERENCES

[1] U.S. Energy Information Agency, *Annual Energy Outlook 2006*, Washington, DC, U.S.A.: DOE/EIA0383(2007).

[2] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay. "Microgrids," *IEEE Power and Energy Magazine,* July/Aug 2007.

[3] J. Apte, L. Lave, S. Talukdar, M.G. Morgan, and M. Ilic, "Electrical blackouts: a systemic problem," *Issues in Science and Technology*, Summer 2004.

[4] C. Gellings, M. Smotyj, and B. Howe, "The future's smart delivery system: meeting the demands for high security, quality, reliability, and availability," *IEEE Power & Energy Magazine*, September/October 2004.

[5] M. Amin, "Powering the 21st century: we can and must modernize the grid," *IEEE Power & Energy Magazine*, March/April 2005.

[6] S. Lee. "For the good of the whole*,"* *IEEE Power & Energy Magazine*, September/October 2007.

[7] European Commission, *European SmartGrids technology platform: vision and strategy for europe's electricity networks of the future.* EUR 22040, Brussels, Belgium, 2006.

[8] R. Lasseter, "Dynamic distribution using (DER): distributed energy resources," *Proc. of IEEE the Power Engineering Society T&D Meeting*, Dallas, TX, U.S.A. May 2006.

[9] C. Marnay and G. Venkataramanan, "Microgrids in the evolving electricity generation and delivery infrastructure," *Proc. of the IEEE Power Engineering Society General Meeting*, Montréal, Canada, June 2006.

[10] R.C. Dugan, M.F. McGranaghan, and H.W. Beaty, *Electric Power Systems Quality*, Second Edition, New York, NY: McGrawHill, 2003.

[11] Siddiqui, Afzal, Chris Marnay, Ryan Firestone, and Nan Zhou. "Distributed Generation with Heat Recovery and Storage," forthcoming in Journal of Energy Engineering special issue on Distributed Generation, vol. 133(3), Sep 2007.

[12] M. Stadler, R. Firestone, D. Curtil, and C. Marnay. "On-Site Generation Simulation with EnergyPlus for Commercial Buildings," in *Proc. of the ACEEE 2006 Summer Study on Energy Efficiency in Buildings,* Asilomar CA, 1319 Aug. 2006.

[13] http://www.eere.energy.gov/buildings/energyplus/

[14] K. Coughlin, R. White, C. Bouldoc, D. Fisher, and G. Rosenquist, "The Tariff Analysis Project: A Database and Analysis Platform for Electricity Tariffs," Berkeley Lab Report LBNL55680, http://tariffs.lbl.gov

[15] http://www.eia.doe.gov

[16] L. Price, C. Marnay, J. Sathaye, S. Murtishaw, D. Fisher, A. Phadke, and G. Franco, "The California Climate Action Registry: Development of Methodologies for Calculating Greenhouse Gas Emissions from Electricity Generation," in *Proc. 2002 ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar Conference Center, Pacific Grove, CA, 1823 Aug. 2002*.