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Optimal Technology Selection and Operation of Microgrids in Commercial Buildings

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Abstract—**The deployment of small (< 1-2 MW) clusters of generators, heat and electrical storage, efficiency investments, and combined heat and power (CHP) applications (particularly involving heat activated cooling) in commercial buildings promises significant benefits but poses many technical and financial challenges, both in system choice and its operation; if successful, such systems may be precursors to widespread microgrid deployment. The presented optimization approach to choosing such systems and their operating schedules uses Berkeley Lab's Distributed Energy Resources Customer Adoption Model [DER-CAM], extended to incorporate electrical storage options. DER-CAM chooses annual energy bill minimizing systems in a fully technology-neutral manner. An illustrative example for a San Francisco hotel is reported. The chosen system includes two engines and an absorption chiller, providing an estimated 11% cost savings and 10% carbon emission reductions, under idealized circumstances.**

Index Terms—**buildings, building management systems, cogeneration, cooling, cost optimal control, dispersed storage and generation, distributed control, optimization methods, power system economics, power system planning**

I. INTRODUCTION

Herein, the working definition of a *microgrid* is: a cluster of electricity sources and (possibly controllable) loads that are connected to the traditional wider power system, or *macrogrid*, but which may, as circumstances or economics dictate, disconnect from it and operate as an island, at least for short periods [1,2,3,4]. The successful deployment of microgrids will depend heavily on the economics of distributed energy resources (DER) in general, and upon the early success of small clusters of mixed technology generation, possibly grouped with storage, controllable loads, and other potential microgrid elements. If clear economic, environmental, and utility system benefits from such early projects are realized, momentum can propel the adoption of added microgrid capabilities as well as precipitate the regulatory adjustments necessary to allow widespread microgrid introduction.

The potential benefits of microgrids are multi-faceted, but from the adopters' perspective there are two major groupings, 1) the cost, efficiency, and environmental benefits (including possible emissions credits) of combined heat and power (CHP), plus 2) the security, quality, reliability, and availability (SQRA) benefits of on-site generation and control. And indeed, the economic, electrically stable, and safe operation and control of such free-standing small-scale systems create new challenges for electrical engineers.

At the same time, it should be noted that growth in electricity demand in the developed countries centers on the residential and commercial sectors in which CHP applications particularly (and SQRA control to a lesser extent) have not hitherto been well developed; furthermore, the relative absence of attention to CHP and SQRA reflects some real technical challenges posed by commercial and residential applications.

This paper reports on the latest in a series of efforts intended to improve the prospects for successful deployment of early microgrid technology in the commercial sector, and the approach could be applied also to residences. In previous work, the Berkeley Lab has developed the Distributed Energy Resources Customer Adoption Model (DER-CAM), which is described in more detail in the appendix [5]. Optimization techniques find both the combination of equipment and its operation over a typical year that minimize the site's total energy bill, typically for electricity plus natural gas. The chosen equipment and its schedule should be economically attractive to a single site or to members of a microgrid consisting of a cluster of sites, and it should be subsequently analyzed in more engineering and financial detail. In this work, electrical storage is added as an option to the prior menu of technology choices, and this capability is demonstrated by the analysis of a prototypical San Francisco hotel.

II. 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

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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 [6]. Their on-site generation capability is often limited to modeling a few generation sources, such as photovoltaic panels (PV), and possibly some heat recovery devices. And typically, the usefulness of the analysis rests heavily on user capability and motivation. Although DER can offer a variety of economic, environmental, and remote macrogrid benefits, such as enhanced demand response, the lack of DER assessment tools is a major hurdle to widespread DER adoption. Developers are lacking the ability to assess the cost, energy use, and carbon and criteria pollutant implications of DER options, and their ability to identify optimal equipment combinations and operating strategies is limited at best. This gap is particularly damaging for DER incorporating CHP because equipment selection and operations can be complex in building applications, often involving multiple technologies, combinations of electricity purchase and self-generation, and highly varied scheduling to follow the occupancy, weather, and other variations in building requirements. Consequently, DER with CHP is rarely explored for buildings too small to justify specialized engineering, e.g. with peak electrical loads approximately below the 1-2 MW range, and particularly waste heat driven cooling is rarely analyzed, despite the importance of cooling to both building requirements and utility system loads in warm climates.

Electrical and/or thermal storage technologies that allow decoupling of electricity generation and heat use in building CHP systems are potentially cost effective. They permit charging and discharging during periods when each is economic, which is obviously potentially beneficial. More subtly, storage allows decoupling of the electricity and heat balances, with the later being much more forgiving. For example, deviations from target building temperature settings for periods of minutes to hours may be acceptable (or at least negotiable, given potential cost savings), whereas practically speaking, AC electrical systems require a precise energy balance at all times. This asymmetry, while it offers potential financial motivation, further complicates analysis of building CHP systems. Only active storage systems are considered in this work, but passive storage, e.g. heat storage in the building shell itself, might also provide benefits. Note the contrast between building CHP applications with traditional (principally industrial) experience. The latter are typically applications with favorable balances of heat and electricity requirements and processes operate in a steady state for extended periods (preferably from an economic perspective, 24/7).

III. 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 [7]. The approach is fully technology-neutral and can include energy purchases, on-site 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 [8,9].

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 on-site 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). The rate at which the state of charge can change is constrained, and the state of charge decays hourly. The parameters used for the electrical and thermal storage models are shown in the following Table 1.

TABLE 1
ENERGY STORAGE PARAMETERS

	description	electrical	thermal
charging efficiency	portion of energy input to storage that is useful	0.9	0.9
decay	portion of state of charge lost per hour	0.001	0.01
maximum charge rate	maximum portion of rated capacity that can be added to storage in an hour	0.25	0.25
maximum discharge rate	maximum portion of rated capacity that can be withdrawn from storage in an hour	0.25	0.25
minimum state of charge	minimum state of charge as a portion of rated capacity	0.3	0

IV. SAN FRANCISCO HOTEL EXAMPLE

An example analysis was completed of a prototypical San Francisco hotel operating in 2004. This hypothetical facility has 23 000 m^2 of floor space and a peak electrical load of 690 kW. Table 2 shows the prices used, which are local Pacific Gas and Electric (PG&E) rates obtained from the Tariff Analysis Projects database [10]. Natural gas prices (shown in two units) for the region were obtained from the Energy Information Administration web site [11]. A marginal carbon emission factor of 140 g/kWh for electricity purchased from PG&E was assumed [12].

The menu of available equipment options to DER-CAM for this analysis together with their cost and performance characteristics is shown in Table 3. 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).

TABLE 2
INPUT ENERGY PRICES

Electricity

	summer		*winter*	
	electricity ($/kWh)	**demand ($/kW)**	**electricity ($/kWh)**	**demand ($/kW)**
all hours		2.55		
on-peak	0.16	11.80		
mid-peak	0.10	2.65	0.11	2.65
off-peak	0.09	0.00	0.09	0.00

Natural Gas

0.03	$/kWh
0.94	$/therm

TABLE 3
MENU OF AVAILABLE EQUIPMENT OPTIONS

Discrete Investments

	fuel cell	**microturbine**		**reciprocating engine**	
capacity (kW)	200	60	100	200	500
installed cost ($/kW)	5005	1826	1576	900	785
installed cost with heat recovery ($/kW)	5200	2082	1769	1250	1050
variable maintenance ($/kWh)	0.029	0.015	0.015	0.015	0.012
efficiency (LHV)	0.35	0.25	0.26	0.295	0.297
lifetime (a)	10	10	10	20	20

Continuous Investments

	electrical storage	**thermal storage**	**absorption chiller**	**solar thermal**	**photovoltaics**
fixed cost ($)	295	10,000	20,000	1,000	1,000
variable cost ($/kW or $/kWh)	193	100	115	150	4,240

DER is not necessarily more energy or carbon efficient than central station generated power bought from the grid.

For example, simple cycle on-site generation of electricity using reciprocating engines at this site would be more carbon intensive than procurement from PG&E; however, using waste heat to offset thermal or electrical loads can improve the overall carbon efficiency. Because incentive payments are usually motivated by efficiency or carbon abatement objectives, qualifying constraints on minimum DER efficiency are often imposed. Although California has these, they are not applied in this analysis.

TABLE 4
ANNUAL RESULTS

	do nothing	invest	low storage price	force low storage price
equipment investment				
reciprocating engines (kW)		2x200	1x200	1x200
absorption chiller (kW)		550	585	585
solar thermal collector (kW)			722	722
electrical storage (kWh)			1100	
thermal storage (kWh)			299	
annual costs (k$)				
electricty	427	127	214	224
NG	32	199	121	126
DG	0	80	67	56
total	459	406	402	406
% savings		11.5%	12.4%	11.5%
annual energy consumption (GWh)				
electricity	3.67	1.18	2	1.94
NG	0.98	6.86	4.16	4.33
annual carbon emissions (t/a)				
emissions	562	503	485	485
% savings		10.4%	13.7%	13.7%

V. RESULTS

Four DER-CAM runs were performed: 1. A *do nothing* case in which all DER investment is disallowed. 2. An *invest* run which finds the optimal DER investment. 3. A *low storage price* run as a sensitivity. 4. Finally, to assess the value of storage systems, a run was performed forcing the same investments as in the low storage price case but in which storage is disallowed.

The major results for these four runs are shown in Table 4. The optimal system consists of two gas engines and an absorption chiller. Relative to the "do nothing" case, 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%).

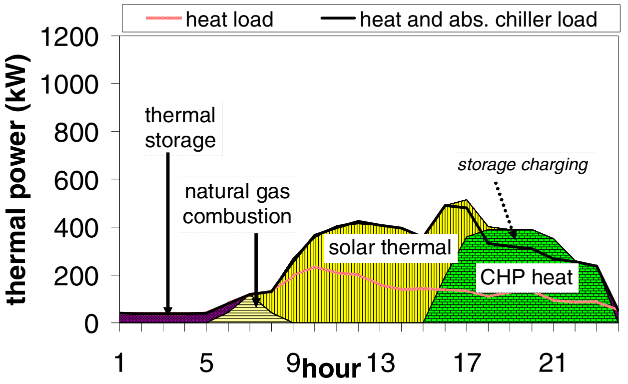

Fig. 1. Low storage price diurnal heat pattern for a January day

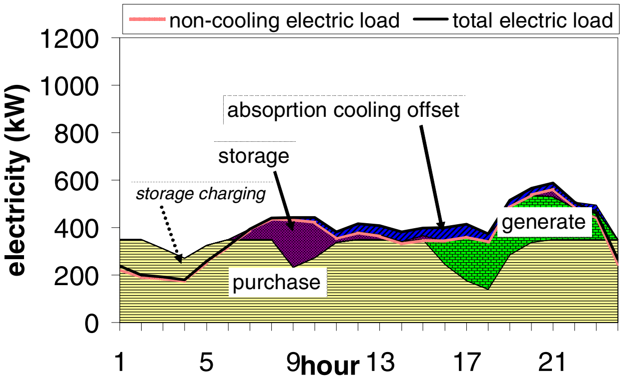

Fig. 2. Low storage price diurnal electricity pattern for a January day

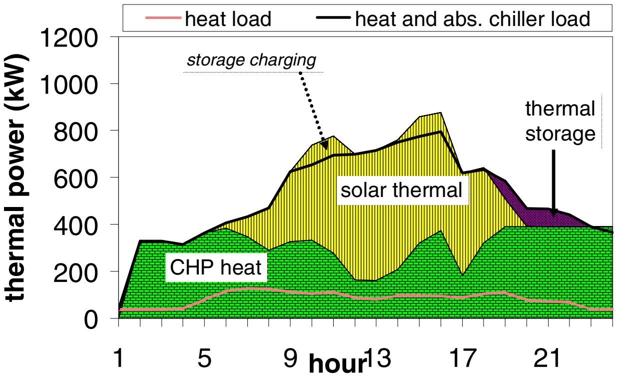

Fig. 3. Low storage price diurnal heat pattern for a July day

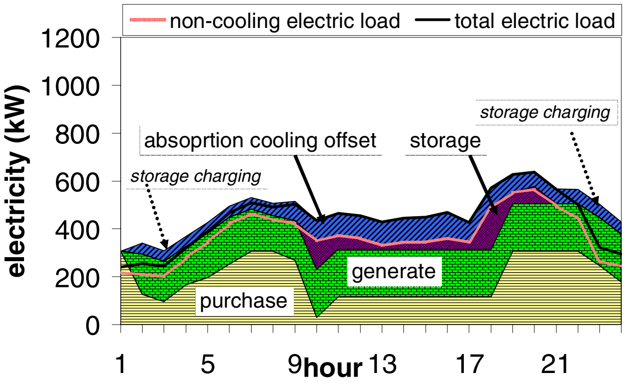

Fig. 4. Low storage price diurnal electricity pattern for a July day

In the 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 compared to the low storage price case. In other words, the added value of the storage and other complexity is very modest in this example.

There is a large difference between the DER systems in the last three cases and yet only minor difference in their energy cost, which suggests a flat objective function near the minimum. It is also likely that results would be sensitive to factors not considered in this analysis, such as risk and site configuration. Please also 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 Figures 1 and 2 above show example DER-CAM operating results for the thermal and electrical balances of the hotel on typical days in January and July 2004 from the low storage price case. Note that the optimal technologies are a 200 kW reciprocating engine, a 585 kW (166 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.

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 electrical loads (Figures 2 and 4) 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. For thermal loads (Figure 1 and 3) 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.

VI. CONCLUSIONS

Limiting the growth of electricity consumption in commercial buildings is particularly important for carbon abatement in developed countries. 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 SQRA benefits. Both thermal and electrical storage capability have been added to DER-CAM, making it a more useful optimization tool for on-site generation selection and operation. The new capabilities have been demonstrated by an analysis of a prototypical San Francisco hotel. Results show the wide range in complexity of optimal systems and the likely carbon emissions reductions. It should be noted that although the example demonstrated herein has primarily focused on the optimal choice of investments, optimization of run-time operational schedules are implicit in the method, and examples are reported as figures.

Incorporation of electrical storage into DER-CAM will facilitate analysis of emerging transportation technologies. For example, the adoption of plug-in hybrids as personal transportation, with their on-board electrical storage offer an on-site load leveling opportunity at minimal additional investment, with potential for additional reduction in carbon emissions. Note that payments for the storage capability of vehicles, as well as for other possible services, such as rapid response load following, could make the economics of such transportation modes more favorable and accelerate their deployment. The integration of such features into DER-CAM is a promising topic for further investigations.

VII. APPENDIX

DER-CAM 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 A1 shows partially disaggregated site enduses on the right-hand side, and energy inputs on the left. As an example, the refrigeration and cooling load may be met in one of multiple ways, including standard electrically powered compressor cooling, direct fire or waste heat activated cooling, or direct gas engine powered compressor cooling (not included in the hotel example analysis above). DER-CAM solves this entire problem optimally and systemically. Figure A2 shows a high level schematic of inputs to and outputs from the model.

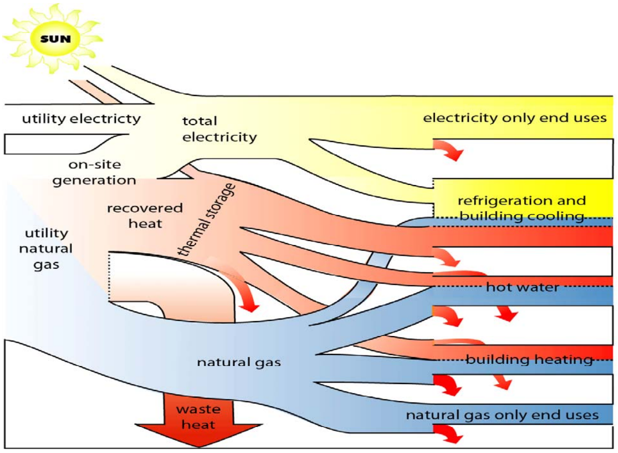

Fig. A1. Energy flows in buildings from fuels to end uses

DER-CAM is particularly suited to evaluating combined heat and power (CHP) opportunities since it selects the optimal combination of DER investment options, fully taking their interdependence into account, e.g., if there is a tradeoff between thermally activated cooling and on-site generator capacity, DER-CAM obtains the combination of the two that minimizes cost. Thus, optimal combinations of equipment involving PV, thermal generation with heat recovery, solar thermal collection, and thermally activated cooling can be identified in a way that would be intractable by trial-and-error testing of all possible combinations.

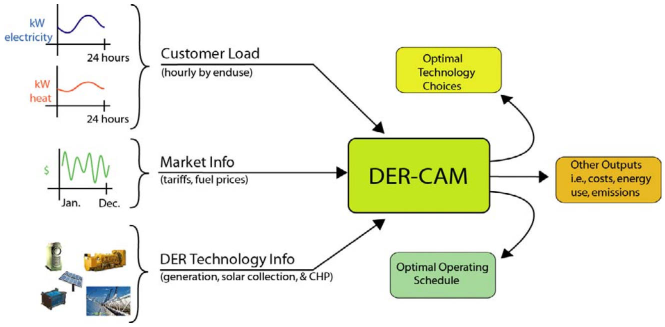

Fig. A2. High level schematic of the inputs and outputs of DER-CAM

DER-CAM is implemented as a mixed integer linear program in the General Algebraic Modeling System (GAMS) using the CPLEX solver. A high level description of the model logic is shown in Figure A3. Siddiqui et al. provides a more detailed description [5]. The run time of a single year execution of DER-CAM that finds the optimal investment decision and hourly on-site generation schedule for a given site is roughly ten minutes on a typical PC.

```
MINIMIZE
   Annual energy cost:
     energy purchase cost
     + amortized DER technology capital cost
     + annual O&M cost
SUBJECT TO
   Energy balance:
     - Energy purchased + energy generated exceeds demand
   Operational constraints:
     - Generators, chillers, etc. must operate within
       installed limits
     - Heat recovered is limited by generated waste heat
   Regulatory constraints:
     - Minimum efficiency requirements
     - Maximum emission limits
   Investment constraints:
     - Payback period is constrained
   Storage constraints:
     - Electricity stored is limited by battery size
     - Heat storage is limited by reservoir size
```

Fig. A3. Optimization problem solved by DER-CAM

VIII. ACKNOWLEDGMENTS

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The authors also acknowledge the contributions of prior members of the DER-CAM development team, Kristina Hamachi LaCommare and Nan Zhou.

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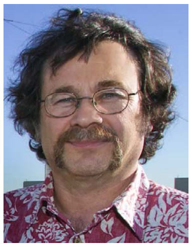
X. BIOGRAPHIES

Bala Chandran is a Ph.D. candidate in the Department of Industrial Engineering and Operations Research at the University of California at Berkeley, and a research assistant at Berkeley Lab. His research interests are in large-scale optimization and modeling, with applications to aviation, supply chain management, telecommunications, and energy resources. He holds a Bachelor of Technology in Civil Engineering from the Indian Institute of Technology, Madras, and a Master of Science in Business and Management from the University of Maryland at College Park.

Ryan Firestone is a Ph.D. candidate in mechanical engineering at the University of California, Berkeley. His doctoral research is on the optimal dispatch of DER in stochastic systems. He received a Bachelors degree from Brown University in 1997 and a Masters degree from the University of Texas El Paso in 2001, both in mechanical engineering. He has researched distributed generation as a research assistant at the Lawrence Berkeley National Laboratory from 2002 until the present.



Chris Marnay is a Staff Scientist in the Electricity Market Studies group within the Energy Environmental Technologies Division of Berkeley Lab. He leads work on modeling of restructured electricity markets, and the organization of small-scale generators into microgrids. He specializes in problems concerning likely future adoption patterns of small scale DER, especially those involving commercial building use of heat activated cooling, and renewables. He has an A.B. in Development Studies, an M.S. in Agricultural and Resource Economics, and a Ph.D. in Energy and Resources, all from the University of California, Berkeley.

Afzal Siddiqui is a Lecturer in the Department of Statistical Science at University College, London. His research interests lie in investment and operational analysis of electricity markets. In particular, he focuses on distributed generation investment under uncertainty, optimal scheduling of distributed generation, real options analysis of renewable energy technologies, and demand response. He holds the following degrees in industrial engineering and operations research: a B.S. from Columbia University, New York, an M.S. and a Ph.D. from the University of California, Berkeley.

Michael Stadler joined Berkeley Lab as a student in 2002, returned as Post-Doctoral Fellow in 2005, and is currently a Visiting Scholar. He also supported the University of California, Berkeley's Pacific Region CHP Application Center, where he conducted site analyses of varied commercial, agricultural, and industrial CHP projects. Previously, he worked with the Energy Economics Group at the Vienna University of Technology, from which he holds a Masters degree in electrical engineering and a Ph.D. *summa cum laude* in energy economics. His fields of research are distributed energy, electricity markets, and demand response.

Giri Venkataramanan (M'92) received a B.E. in electrical engineering from the Government College of Technology, Coimbatore, India, an M.S. from the California Institute of Technology, Pasadena, and a Ph.D. from the University of Wisconsin, Madison in 1986, 1987 and 1992 respectively. After teaching at Montana State University, Bozeman, he returned to Madison as a faculty member in 1999, where his research continues in various areas of electronic power conversion. He serves as Associate Director of the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC). He holds six U.S. patents and has coauthored more than a hundred technical publications.