LBNL-51771

Effects of a Carbon Tax on Combined Heat and Power Adoption by a Microgrid

Chris Marnay, Jennifer L. Edwards, Ryan M. Firestone, Srijay Ghosh, Afzal S. Siddidqui, and Michael Stadler

Environmental Energy Technologies Division
Ernest Orlando Lawrence Berkeley National Laboratory
1 Cyclotron Road,
Berkeley, CA 94720-8061

October 2002

In the proceedings of the International Symposium on Distributed and Market Aspects, Royal Institute of Technology Department of Electrical Engineering, Stockholm, Sweden - October 2-4, 2002

The work described in this paper was funded by the Assistant Secretary of Energy Efficiency and Renewable Energy, Office of Power Technologies, under the U.S. Department of Energy Contract No. DE-AC03-76SF00098.

Effects of a Carbon Tax on Combined Heat and Power Adoption by a Microgrid

Chris Marnay[*], Jennifer L. Edwards, Ryan M. Firestone, Srijay Ghosh, Afzal S. Siddiqui, and Michael Stadler

Abstract

This paper describes the economically optimal adoption and operation of distributed energy resources (DER) by a hypothetical California microgrid (µGrid) consisting of a group of commercial buildings over an historic test year, 1999. The optimisation is conducted using a customer adoption model (DER-CAM) developed at Berkeley Lab and implemented in the General Algebraic Modeling System (GAMS). A µGrid is a semiautonomous grouping of electricity and heat loads interconnected to the existing utility grid (macrogrid) but able to island from it. The µGrid minimises the cost of meeting its energy requirements (consisting of both electricity and heat loads) by optimising the installation and operation of DER technologies while purchasing residual energy from the local combined natural gas and electricity utility. The available DER technologies are small-scale generators (< 500 kW), such as reciprocating engines, microturbines, and fuel cells, with or without CHP equipment, such as water- and space- heating and/or absorption cooling. By introducing a tax on carbon emissions, it is shown that if the µGrid is allowed to install CHP-enabled DER technologies, its carbon emissions are mitigated more than without CHP, demonstrating the potential benefits of small-scale CHP technology for climate change mitigation. Reciprocating engines with heat recovery and/or absorption cooling tend to be attractive technologies for the mild southern California climate, but the carbon mitigation tends to be modest compared to purchasing utility electricity because of the predominance of relatively clean generation in California.

1. Introduction

1.1 Microgrid Concept

The analysis included in this paper is built on the vision that future electric power systems will not be organised solely as centralised systems as they are today. Rather, a significant share of electricity will be generated and consumed locally within microgrids (µGrids) that are designed and controlled to meet local requirements (see Lasseter et al. 2002). µGrids will operate according to their own protocols and standards, will match power quality and reliability to individual load requirements, and will exploit efficiency improving technologies, especially those involving combined heat and power (CHP).

The expectation that distributed energy resources (DER) will emerge over the next decade or two to reshape the way in which electricity is supplied stems from the following hypotheses:

1. small-scale generating technology will improve its cost and performance
2. volatile wholesale electricity and fuel markets, and other limits, will impede continued expansion of the existing electricity supply infrastructure, or macrogrid
3. the potential for application of small-scale CHP technologies will tilt power generation economics in favour of generation based closer to heating and/or cooling loads
4. customers' requirements for service quality and reliability levels which cannot be met only by conventional grid connection will expand
5. power electronics will enable interconnection of asynchronous devices with the existing power system and operation of semi-autonomous systems allowing seamless interaction of DER with the main power system.

This research is built upon the fundamental concept of the µGrid, which could form a component of a more decentralised power system. A µGrid consists of a localised semi-autonomous grouping of loads, generation, and storage operating under co-ordinated local control, either active or passive. The µGrid is connected to the current power system, or

[*] Staff Scientist, Ernest Orlando Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, MS 90-4000, Berkeley, CA 94720-8061, USA.
tel: +1.510.486.7028
fax: +1.510.486.7976
e-mail: C_Marnay@lbl.gov
web: der.lbl.gov

macrogrid, in a manner that allows it to appear to the wider grid as a *good citizen*; that is, the μGrid performs as a legitimate entity under grid rules, e.g., as what is currently considered a normal electricity customer or generating unit.

Traditional power system planning and operation hinges on the assumption that the selection, deployment, and financing of generating assets will be tightly coupled to changing requirements, and that it will rest in the hands of a centralised authority. By contrast, μGrids will develop in accordance with their independent local incentives. Avoided cost electricity purchases was the first U.S. step towards abandoning the centralised paradigm, and the ongoing deregulation of central generation represents the second. The emergence of μGrids and other locally controlled systems represents the third and will be the most technically fundamental to customers. Because μGrids will develop their own independent operational standards and expansion plans, the overall growth pattern of the power system will be significantly different. In other words, the power system will be expanding more in accordance with dispersed independent goals. Nevertheless, exchange of power between the μGrid and the macrogrid can be made whenever there are economic benefits for such a transaction, and it is technically feasible.

1.2 Impact of CHP Inclusion on DER Adoption

The additional consideration of CHP in distributed generation greatly increases the complexity of both the modelling problem and its physical manifestation. While it may seem that electricity from any source can be supplied to a customer via the existing electrical system of a building, requiring only a power electronics interface between the generators and the building wiring, the reality is more complex. This is in part because of the need to allow bidirectional power flow and, possibly, to actively control it. While CHP applications may require that proper pumps and plumbing be installed to transfer the hot operating fluid to the thermal points of use, the logistics and economics of μGrids will likely favour placement of generators adjacent to suitable heat sinks whenever possible. Although CHP does increase the complexity of the system, the economic savings introduced can tip the economic scales in favour of on-site generation. In addition, emissions can be reduced because overall energy efficiency is improved; this makes CHP even more attractive when carbon taxes or other emission taxes are considered. In this example, DER-CAM consistently chose to implement CHP where available.

1.3 Approach of Current Work

The approach taken in this work is strictly customer oriented. This stands in contrast to much past study of DER, which has tended to consider DER as an additional option available to utility planners and systems (see Weinberg et al. 1991). A recent study evaluated the applicability of the μGrid in organising on-site generation for industrial application (see Piagi et al. 2001). Furthermore, past work has evaluated the benefits of DER in terms of improved power system performance rather than in terms of enhanced customer control (see van Sambeek 2000). The starting point here is to minimise the cost of meeting the known electrical and heat loads of a μGrid. Techniques for optimally solving the cost minimizing electricity supply problem have been developed over many years for planning and operating utility scale systems. Since the customer-scale problem is essentially similar to the utility-scale problem, established methods can be readily adapted. In this study, however, the approach is significantly extended to jointly optimise the potential use of CHP by the μGrid. While the patterns of potential customer adoption and generation are interesting in themselves, this model is further used to answer two specific policy questions:

- How does the presence of a carbon tax affect the μGrid's decision to invest in DER technologies?
- Which technologies are more conducive to carbon emissions abatement given the imposition of a carbon tax?

2. Mathematical Model

2.1 Introduction

In this section, the DER Customer Adoption Model (DER-CAM) is presented, including an overview of the present version of the model's mathematical formulation. While this model has been used extensively by Berkeley Lab researchers and results have been previously reported (see Marnay et al. 2000), the current version additionally incorporates CHP-enabled technologies and carbon taxation. All versions of the model have been programmed in GAMS (General Algebraic Modeling System)[1]. The results presented are not intended to represent a definitive analysis of the benefits of DER adoption, but rather as a demonstration of the current DER-CAM. Developing estimates of realistic customer costs is an important area in which improvement is both essential and possible, and is being actively pursued by the authors in other work.

2.2 Model Description

The model's objective function is to minimise the cost of supplying electricity to a specific μGrid during a given year by optimising the distributed generation of part or its entire electricity requirement. In order to attain this objective, the following questions must be answered:

- Which distributed generation technology (or combination of technologies) should the μGrid install?
- What is the appropriate level of installed capacity of these technologies that minimises the cost of meeting the μGrid's electricity requirement?
- How should the installed capacity be operated in order to minimise the total bill for meeting the μGrid's electricity load?

The essential inputs to DER-CAM are:

- the μGrid's electricity and heating load profiles
- the default tariff in this work is one from the San Diego Gas and Electric Company (SDG&E, utility, or disco)
- capital, operating and maintenance (O&M), and fuel costs of the various available DER technologies, together with the interest rate on customer investment
- rate of carbon emissions from the macrogrid, DER technologies, and burning of natural gas to meet thermal loads
- thermodynamic parameters governing the use of CHP-enabled DER technologies
- carbon tax rates

Outputs to be determined by the optimisation are the cost minimising:

- technology (or combination of technologies) and their respective capacities
- hourly operating schedules for installed equipment
- total cost of supplying the energy requirement through either DER or macrogrid generation, or typically, a combination of the two

Of the important assumptions that follow, the first three tend to understate the benefit of DER, while the fourth overstates it:

1. Customer decisions are taken based only on direct economic criteria, i.e., the only benefit that the μGrid can achieve is a reduction in its energy bill.
2. The μGrid is not allowed to generate more electricity than it consumes. On the other hand, if more electricity is consumed than generated, then the μGrid will buy from the macrogrid at the default tariff rate. No other market opportunities, such as sale of ancillary services and load interrupts, are considered.
3. Reliability and power quality benefits, and economies of scale in O&M costs for multiple units of the same technology are not taken into account.
4. Manufacturer claims for equipment price and performance are accepted without question. Some of the permitting and other costs are not considered in the capital cost of equipment, nor are start-up and other operating costs.

2.3 Mathematical Formulation

This section describes intuitively the core mathematical problem solved by DER-CAM. First, the input parameters are listed, and the decision variables are defined. Next, the optimisation problem is described.

2.3.1 Variables and Parameters Definition

2.3.1.1 Input Parameters

Time Scale Definition

Name	Definition
Day Type	Week or weekend
Season	Summer (May through September, inclusive) or winter (the remaining months)
Period	On-peak (hours of the day 1200 through 1800, inclusive, during summer months, and 1800 through 2000 during the winter), mid-peak (0700 through 1100 and 1900 through 2200 during the summer, and 0700 through 1700 and 2100 through 2200 during the winter), or off-peak (0100 through 0600 and 2100 through 2200 during all months)

Customer Data

Name	Description
$Cload_{m,t,h,u}$	Customer load (electricity or heating) in kW for end-use *u* during hour *h*, day type *t* and month *m* (end-uses are electric-only, cooling, space-heating, water-heating, and natural-gas-only)

Market Data[2]

Name	Description
$RTPower_{s,p}$	Regulated demand charge under the default tariff for season *s* and period *p* ($/kW)
$RTEnergy_{m,t,h,u}$	Regulated tariff for electricity purchases during hour *h*, type of day *t*, month *m*, and end-use *u* ($/kWh)
$RTCDCharge_m$	Regulated tariff charge for coincident demand, i.e., residual electric-only or cooling load, that occurs at the same time as the monthly system peak during month *m* ($/kW)
$RTCCharge$	Regulated tariff customer charge ($)
$RTFCharge$	Regulated tariff facilities charge ($/kW)
$NGBSF_m$	Natural gas basic service fee for month *m* ($)
$CTax$	Tax on carbon emissions ($/kg)
$MktCRate$	Carbon emissions rate from marketplace generation (kg/kWh)
$NGCRate$	Carbon emissions rate from burning natural gas to meet heating and cooling loads (kg/kWh)
$NatGasPrice_{m,t,h}$	Natural gas price during hour *h*, type of day *t*, and month *m* ($/kJ)

Distributed Energy Resource Technologies Information

Name	Description
$DERmaxp_i$	Nameplate power rating of technology *i* (kW)
$DERlifetime_i$	Expected lifetime of technology *i* (a)
$DERcapcost_i$	Turnkey capital cost of technology *i* ($/kW)
$DEROMfix_i$	Fixed annual operation and maintenance costs of technology *i* ($/kW)
$DEROMvar_i$	Variable operation and maintenance costs of technology *i* ($/kWh)
$DERhours_i$	Maximum number of hours technology *i* is permitted to operate during the year (h)
$DERCostkWh_{i,m}$	Production cost of technology *i* during month *m* ($/kWh)
$CRate_i$	Carbon emissions rate from technology *i* (kg/kWh)
$S(i)$	Set of end-uses that can be met by technology *i*

Other Parameters

Name	Description
$IntRate$	Interest rate on DER investments (%)
$Solar_{m,h}$	Average fraction of maximum solar insolation received (%) during hour *h* and month *m* used to power photovoltaic (PV) cells
$NGHR$	Natural gas heat rate (kJ/kWh)
$t(m)$	Day type in month *m* when system demand peaks
$h(m)$	Hour in month *m* when system demand peaks
α_i	The amount of heat (in kW) that can be recovered from unit kW of electricity that is generated using DER technology *i* (this is equal to 0 for all technologies that are not equipped with either a heat exchanger or an absorption chiller)

β_u	The amount of heat (in kW) generated from unit kW of natural gas purchased for end-use u (since the electricity-only load never uses natural gas, the corresponding β_u value equals 0)
$\gamma_{i,u}$	The amount of useful heat (in kW) that can be allocated to end-use u from unit kW of recovered heat from technology i (note: since the electricity-only and natural-gas-only loads never use recovered heat, the corresponding $\gamma_{i,u}$ values equal 0)

2.3.1.2 Decision Variables

Name	**Description**
$InvGen_i$	Number of units of technology *i* installed by the customer
$GenL_{i,m,t,h,u}$	Generated power by technology *i* during hour *h*, type of day *t*, month *m* and for end-use *u* to supply the customer's load (kW)
$GasP_{m,t,h,u}$	Purchased natural gas during hour *h*, type of day *t*, and month *m* for end-use *u* (kW)
$DRLoad_{m,t,h,u}$ [3]	Purchased electricity from the distribution company by the customer during hour *h*, type of day *t*, and month m for end-use *u* (kW)
$\mathrm{Re}cHeat_{i,m,t,h,u}$	Amount of heat recovered from technology *i* that is used to meet end-use *u* during hour *h*, type of day *t*, and month *m* (kW)

2.3.2 Problem Formulation

It is assumed that the μGrid acquires the residual electricity that it needs beyond its self-generation from the distribution company (disco) at the regulated tariff[4]. The mathematical formulation of the problem follows:

$$
\begin{aligned}
\min_{\substack{InvGen_i \\ GenL_{i,m,t,h,u} \\ GasP_{m,t,h,u} \\ \mathrm{Re}cHeat_{i,m,t,h,u}}} \quad & \sum_m RTFCharge \cdot \max\left(\sum_{u \in \{electric-only,cooling\}} DRLoad_{m,t,h,u} \right) + \sum_m RTCCharge \\
& + \sum_s \sum_{m \in s} \sum_p RTPower_{s,p} \cdot \max\left(\sum_{u \in \{electric-only,cooling\}} DRLoad_{m,(t,h) \in p,u} \right) \\
& + \sum_m \sum_{u \in \{electric-only,cooling\}} RTCDCharge_m \cdot DRLoad_{m,t(m),h(m),u} \\
& + \sum_m \sum_t \sum_h \sum_u DRLoad_{m,t,h,u} \cdot \left(RTEnergy_{m,t,h} + CTax \cdot MktCRate \right) \\
& + \sum_i \sum_m \sum_t \sum_h \sum_u GenL_{i,m,t,h,u} \cdot DERCostkWh_i + \sum_i \sum_m \sum_t \sum_h \sum_u GenL_{i,m,t,h,u} \cdot DEROMvar_i \\
& + \sum_i \sum_m \sum_t \sum_h GenL_{i,m,t,h} \cdot CTax \cdot CRate_i \\
& + \sum_i InvGen_i \cdot \left(DERcapcost_i \cdot AnnuityF_i + DEROMfix_i \right) + \sum_m NGBSF_m \\
& + \sum_m \sum_t \sum_h \sum_u GasP_{m,t,h,u} \cdot NGHR \cdot \left(NatGas\,\mathrm{Pr}ice_{m,t,h} + CTax \cdot NGCRate \right)
\end{aligned}
\tag{1}
$$

Subject to:

$$
Cload_{m,t,h,u} = \sum_i GenL_{i,m,t,h,u} + DRLoad_{m,t,h,u} + \beta_u \cdot GasP_{m,t,h,u} + \sum_i \left(\gamma_{i,u} \cdot \mathrm{Re}cHeat_{i,m,t,h,u} \right) \forall\, m,t,h,u \tag{2}
$$

$$\sum_{u} GenL_{i,m,t,h,u} \leq InvGen_i \cdot DER\max p_i \quad \forall i,m,t,h \tag{3}$$

$$AnnuityF_i = \frac{IntRate}{\left(1 - \frac{1}{(1+IntRate)^{DERlifetime_i}}\right)} \forall i \tag{4}$$

$$\sum_{u} GenL_{j,m,t,h,u} \leq InvGen_j \cdot DER\max p_j \cdot Solar_{m,h} \quad \forall m,t,h \;\; if \;\; j \in \{PV\} \tag{5}$$

$$\sum_{m}\sum_{t}\sum_{h}\sum_{u} GenL_{i,m,t,h,u} \leq InvGen_i \cdot DER\max p_i \cdot DERhours_i \;\; \forall i \tag{6}$$

$$\sum_{u} \mathrm{Re}\,cHeat_{i,m,t,h,u} \leq \alpha_i \cdot \sum_{u} GenL_{i,m,t,h,u} \;\forall i,m,t,h \tag{7}$$

$$\mathrm{Re}\,cHeat_{i,m,t,h,u} = 0 \quad \forall i,m,t,h \quad if \quad u \notin S(i) \tag{8}$$

$$GenL_{i,m,t,h,u} = 0 \quad \forall i,m,t,h \quad if \quad u \in \{space - heating, water - heating, natural\text{-}gas\text{-}only\} \tag{9}$$

$$DRLoad_{m,t,h,u} = 0 \quad \forall m,t,h \quad if \quad u \in \{space - heating, water - heating, natural - gas - only\} \tag{10}$$

Equation (1) is the objective function that states that the µGrid will try to minimise total energy cost, consisting of facilities and customer charges, monthly demand charges, coincident demand charges, and disco energy charges inclusive of carbon taxation. In addition, the µGrid incurs on-site generation fuel and O&M costs, carbon taxation on on-site generation, and annualised DER investment costs. Finally, for natural gas used to meet heating and cooling loads directly, there are variable and fixed costs (inclusive of carbon taxation).

The constraints to this problem are expressed in equations (2) through (10):

- equation (2) enforces energy balance (it also indicates the means through which the load for energy end-use *u* may be satisfied)
- equation (3) enforces the on-site generating capacity constraint
- equation (4) annualises the capital cost of owning on-site generating equipment
- equation (5) constrains technology *j* to generate in proportion to the solar insolation if it is a PV cell
- equation (6) places an upper limit on how many hours each type of DER technology can generate during the year[5]
- equation (7) limits how much heat can be recovered from each type of DER technology
- equation (8) prevents the use of recovered heat by end-uses that cannot be satisfied by the particular DER technology
- equations (9) and (10) are boundary conditions that prevent electricity from being used directly to meet heating loads

3. Input Data

3.1 Customer Loads

DER-CAM is run for a hypothetical µGrid over the test year of 1999. The µGrid is composed of four typical southern California commercial electricity customers acting as one (a supermarket, an office, a retail store, and a shopping mall). The µGrid derives some advantage from the fact that when the customers pool their loads, the resulting load is flatter, and therefore, less exposed to tariff demand charges than the individual it actively (see Figure 1 and Figure 2). The individual customer electricity and thermal loads for California in the year 1998 were extracted from a variety of sources, including enduse metered loads from a distribution utility monitoring program, simulations from DOE2[6], and the Maisy[7] data base (see Marnay et al. 2001). About 35% of energy consumption is for electricity-only enduses such as lighting that cannot be met by CHP.

3.2 Utility Tariff and Carbon Emissions

Parameters of the SDG&E tariff used in this study are summarised in Table 1 Additionally, there is a monthly customer charge of US$43.50. The time period definitions are shown in Section 2.3.1.1. An unusual feature of the tariff is the dual demand (peak power) charges, one (*power charge*) at the time of the customer's individual peak and a second (*coincident demand*) at the time of the overall system peak.

Table 1. SDG&E Tariff Information for 1999

Tariff Type	Season	Load Period	Power Charge ($/kW)	Coincident Demand Charge ($/kW)	Energy Charge ($/kWh)
TOU	summer	on	5.094	13.23	0.10052
TOU	summer	mid	5.094	13.23	0.06883
TOU	summer	off	5.094	13.23	0.05562
TOU	winter	on	4.856	4.86	0.09652
TOU	winter	mid	4.856	4.86	0.06733
TOU	winter	off	4.856	4.86	0.05283

The assumed carbon emission factor for purchased electricity is 0.13 kg/kWh. The average carbon emissions rate for electricity supplied to Californians probably lies in the 0.105-0.110 kg/kWh range, but rates are much higher in the southern part of the state because of its higher dependence on imported coal generated electricity (see Price et al. 2002). As a result, the 0.13 assumption is low for SDG&E, but is chosen to help demonstrate the overall California situation. Marginal carbon emission factors are most likely much higher, and an analysis in which the utility charged a marginal rather than average carbon tax on delivered electricity would significantly benefit DER.

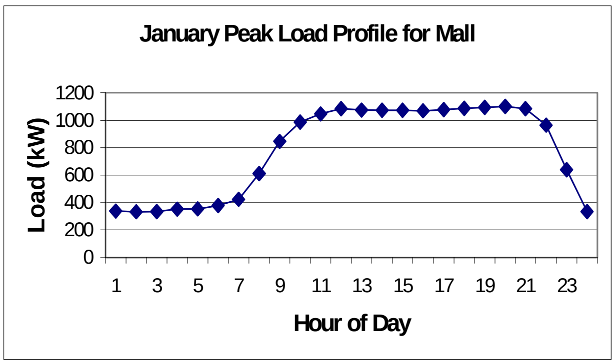

Figure 1. Mall Electricity-Only Load for January

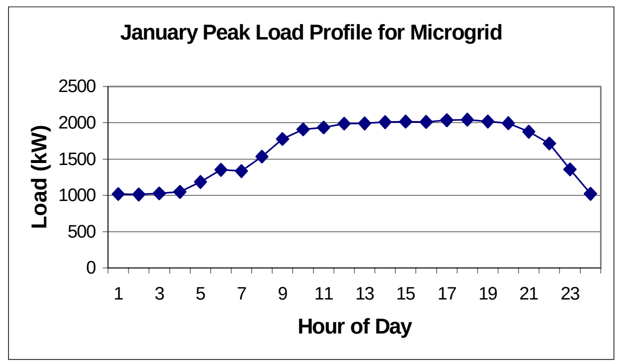

Figure 2. µGrid Electricity-Only Load for January

3.3 DER Technologies

The generating technologies available to the µGrid are microturbines manufactured by Capstone, phosphoric acid fuel cells made by ONSI (also known as UTC fuel cells), diesel backup generators manufactured by Cummins/Onan, Katolight natural gas reciprocating generators, and photo-voltaic (PV) cells. For each of these technologies, the nameplate power of technology (kW), technology lifetime (a), turnkey cost (US$/kW), operational and maintenance fixed (US$/kWa) and variable costs (US$/kWh), heat rate (kJ/kWh), and fuel requirements (gas/diesel/sun) are provided (see Table 2 for details). CHP-enabled technologies have higher turnkey costs to account for the additional expenses associated with purchase and installation of heat exchangers, absorption chillers, and the related infrastructure. The National Renewable Energy Laboratory (NREL, http://www.nrel.gov) provides solar insolation data. In addition, for technologies equipped with heat exchangers and/or absorption chillers, thermodynamic parameters (as defined in the "Other Parameters" table of Section 2.3.1.1) that govern the efficiency of electricity generation and heat recovery, α_i and $\gamma_{i,u}$, have been estimated. For example, α_i varies between 0.72 and 2.67, and $\gamma_{i,u}$ is 0.8 for space- and water-heating, 0.11 for cooling, and zero for both electricity-only and natural-gas-only end-uses, regardless of the technology. The conversion efficiency for burning of natural gas to meet end-uses directly, i.e., β_u, is assumed to be 0.8 for all end-uses except for electricity-only, for which it is zero. In other words, it is assumed that the µGrid already has gas-fired absorption cooling capability.

3.4 Fuel Data

The other data needed to run DER-CAM are fuel prices, carbon emissions rate, and the costs associated with it. For each fuel, its price (US$/kJ) and carbon emissions rate (kg/kJ) is provided. Natural gas prices for 1999 were very stable, with the monthly price varying between US$4.03/GJ and US$5.56/GJ, and a low volatility[8] of 8.8%. The volatility of the diesel price during a year is even smaller, and therefore, the diesel price is assumed constant at US$8.46/GJ.

4. Results

In this section, the effects of carbon taxation on DER adoption, particularly with CHP, and carbon emissions are discussed. In order to determine the interaction between carbon taxation and availability of DER technologies, the DER-CAM model in GAMS is executed for three scenarios:

- do-nothing
- install-no-CHP
- install-CHP

In the first scenario, the µGrid is not permitted to install any DER technologies and must fulfil all of its energy needs through utility purchases. In the second scenario, the adoption of DER technologies is allowed, but without the CHP option, whereas in the third scenario, there are no restrictions regarding the selection of technologies.

The results indicate that carbon emissions are reduced the most through the installation of CHP-enabled technologies. Indeed, without CHP, it becomes more costly to use on-site generation with a high carbon tax, so the µGrid switches to using the slightly less polluting macrogrid to meet its electricity needs. At the same time, it burns natural gas to meet its heating loads. Together, these two activities imply an average carbon emissions rate of about 0.08 kg/kWh for meeting the total energy demand (heat and electrical). In this work, the utility average emissions rate is assumed to be 0.13 kg/kWh and that for direct burning of natural gas, it is 0.05 kg/kWh, while about 35% of energy consumption is for primarily electricity-only enduses[9]. With CHP, however, the µGrid is able to use recovered energy to meet its heating loads, thereby implying that it emits very little carbon in meeting its heating loads. Consequently, DER technologies with carbon emissions rates of 0.17 kg/kWh (such as the microturbines in Table 2) in meeting the electricity-only load become preferable to the macrogrid. Indeed, because virtually no incremental carbon emissions are produced in meeting the heating load, the average carbon emissions rate drops below 0.08 kg/kWh (the value associated with the "do-nothing" scenario). In fact, in the case with CHP, almost two-thirds of the µGrid's energy demand is met via DER, on average three times as much as the install-no-CHP case. As a result, the energy efficiency of the system is greater, implying that fewer resources are needed to satisfy the same level of energy consumption.

4.1 Effect of Carbon Tax on DER Generation

Intuitively, one would expect the implementation of carbon taxation to encourage adoption of DER technologies. Indeed, the only effective recourse to offset increasing carbon taxes is to install on-site generators that have lower carbon emissions rates than the macrogrid. In Figure 3, however, the level of installed DER capacity stays constant for the two adoption scenarios over a large range of carbon tax levels. This is because most of the available DER generators have higher carbon emissions rates than the macrogrid. Moreover, the few that do have lower carbon emissions rates, such as PV cells, have high turnkey costs that preclude their adoption unless the carbon tax approaches US$1000/t. For a large range of carbon tax levels in the "install-no-CHP" scenario, the µGrid installs one 500 kW gas-fired backup engine (Katolight 500FGZ4), which has a low turnkey cost, but a high rate of carbon emissions. Therefore, the µGrid self-provides a declining percentage of its own energy needs as the carbon tax increases (see Figure 4). In other words, the one on-site generator is used less frequently as the tax is increased. The reason it is not abandoned entirely is probably because of the benefits of avoiding the high demand charges.

Similarly, in the "install-CHP" scenario, the level of adopted capacity also stays constant, with eight units of the 30 kW CHP-enabled microturbine (Capstone LP330) and two 55 kW gas-fired backup engines (Katolight 55FGG4) frequently installed. The difference from the non-CHP installation scenario is that the µGrid is still finds it economical to meet most of its energy (electricity and heating) needs on-site even as the carbon tax increases (see Figure 4). Indeed, although the increasing carbon tax makes on-site electricity production less attractive than macrogrid generation, the µGrid can now use recovered heat to meet much of its heating load. This tilts the balance back in favour of (CHP-enabled) DER technology generation as a strategy for reducing carbon emissions. The lower energy costs achieved through CHP-enabled DER generators attest to its efficiency (see Figure 5).

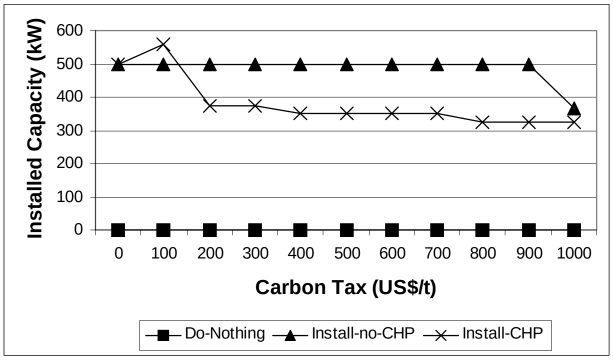

Figure 3. Effect of Carbon Tax on Installed Capacity

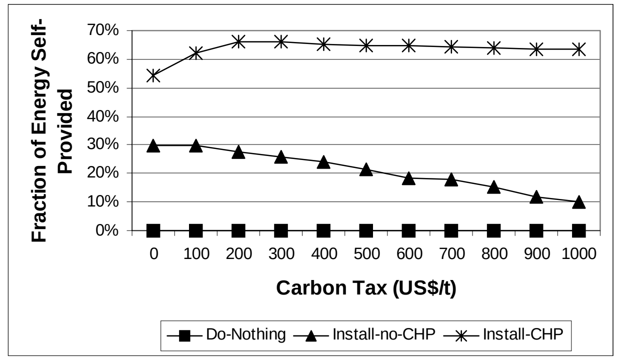

Figure 4. Effect of Carbon Tax on Self-Provision of Energy

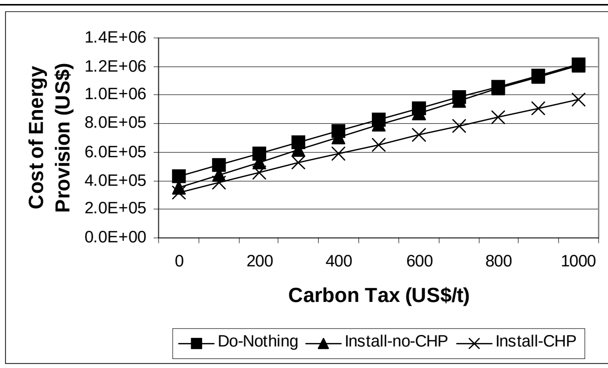

Figure 5. Effect of Carbon Tax on Total Cost

4.2 Effect of Carbon Tax on Emissions

The carbon tax has a similar effect on carbon emissions as on DER generation. While the "do-nothing" scenario leaves carbon emissions unchanged, in the "install-no-CHP" scenario, carbon emissions decrease slightly as the carbon tax increases (see Figure 6). The overall impact on carbon emissions is minor, however, because initial carbon emissions with most DER technologies are greater than with macrogrid generation. Therefore, as the carbon tax increases, the μGrid relies more on the macrogrid until carbon taxes approach US$1000/t, at which point it installs PV cells. Nevertheless, even the drastic measure of adopting high capital cost PV technologies results in only a 8% decrease in carbon emissions from the "do-nothing" level (see Figure 7). Since carbon tax levels of less than US$100/t have no effect on emissions, the analysis considers values up to US$1000/t.

By contrast, the effect of carbon taxation on carbon emissions in the "install-CHP" scenario is immediate and profound. Indeed, for even a relatively low carbon tax of US$100/t, carbon emissions are reduced by over 5% from their initial level (see Figure 8). Even without a carbon tax, the use of CHP-enabled DER equipment permits the μGrid to attain almost a 10% decrease in carbon emissions relative to the "do-nothing" scenario (see Figure 7). This illustrates the potential for reducing carbon emissions at relatively low levels of carbon taxation via CHP-enabled DER generation. The use of CHP itself is facilitated by the μGrid concept which allows loads to be pooled and recovered heat to be utilised where it is most needed. Thus, from a policy perspective, carbon emissions abatement is more effective at publicly acceptable levels of carbon taxation when CHP-enabled DER equipment is installed.

An analysis of the origins of carbon emissions indicates a similar trend. In the "do-nothing" scenario, carbon emissions are produced in almost equal proportion by the macrogrid and natural gas burned to meet the heating loads (see Figure 9). By installing DER technologies without CHP capability, the μGrid's burden of carbon emissions production initially shifts to self-generation before moving off-site to the macrogrid as the carbon tax increases (see Figure 10). The carbon-intensity of thermal on-site generation is reflected in the fact that even though it provides only about 10% of the energy used by the system (see Figure 4), it, nevertheless, produces over 20% of the carbon emissions. This imbalance is redressed by the introduction of CHP, which is able to use recovered heat, thereby obviating the need for burning natural gas (see Figure 11). Here, about 55% of the µGrid's carbon emissions are from DER activities, even as DER produces almost 65% of the energy.

While certain emerging technologies, such as PV cells, also mitigate carbon emissions, their efficiency and widespread adoption is negated by their currently high turnkey costs. Indeed, the PV technologies adopted in the "install-no-CHP" scenario are not as effective as the CHP-enabled technologies in the "install-CHP" scenario even at high levels of carbon taxation, i.e., US$1000/t (see Figure 12). Hence, policymakers interested in carbon emissions mitigation would be advised to remove obstacles for CHP-enabled DER generation.

4.3 Energy Efficiency

Besides being more cost-effective and less carbon-intensive than both the macrogrid and DER technologies alone, CHP is, of course, also more energy efficient. This implies that it uses less fuel to satisfy a unit of energy load than the other options available. For the purposes of this study, the energy efficiency of the system is calculated as follows:

$$Efficiency = \frac{AnnualUsefulEnergy}{AnnualFuelConsumption}$$

The *annual useful energy* of the system is simply the summation of the hourly energy end-use loads. In order to meet these loads, fuel is consumed, whether to meet heating loads or to run generators to provide electricity. . The *annual fuel consumption* is the adjusted sum of energy consumed, where the adjustments reflect the coefficient of performance of the technology (COP), e.g., a COP of 5 is assumed for compressor cooling. The recovered heat that is available to meet water- and space-heating loads via CHP-enabled DER equipment boosts the energy efficiency of the system because incremental fuel consumption is not necessary to meet these loads. Indeed, the increase in the system's energy efficiency for the "install-CHP" scenario (see Figure 13) coincides with the increasing amounts of energy self-provided via CHP (see Figure 4).

For the "install-no-CHP" scenario, system energy efficiency stays constant for most values of the carbon tax because only the 500 kW generator is utilised. Since its efficiency is similar to that of the macrogrid, the overall system energy efficiency is virtually identical to that of the "do-nothing" scenario. Only when the carbon tax reaches US$1000/t does the system energy efficiency increase for the "install-no-CHP" scenario as some PV technologies are installed. Even then, a CHP-enabled system is more energy efficient due to its ability to meet heating loads via recovered heat.

5. Conclusions

In this paper, an economic model is constructed to determine the effect of carbon taxation on DER technology adoption and carbon emissions by a hypothetical southern California µGrid composed of commercial enterprises. The µGrid's objective is to minimise the cost of meeting its energy load through either local utility purchases or on-site generation. When the resulting optimisation problem is solved using GAMS, it is found that CHP-enabled DER technologies are more effective at reducing carbon emissions than the macrogrid (or even PV) over a large range of carbon tax values, given the cost minimising objectives of the µGrid.

It is found that implementing DER technologies that are not CHP-enabled is no more effective at reducing carbon emissions than using the macrogrid. This is because these DER technologies have similar carbon emissions rates and energy efficiencies as the macrogrid, which limits their ability to reduce carbon emissions. Average macrogrid generation delivered is even less carbon emitting than on-site generation fired by natural gas, and so the ability of on-site generation to compete is severely constrained, especially when carbon taxes inflate the efficiency differential between on-site and utility power generation. Only when the carbon tax reaches high levels, e.g., US$1000/t, do DER technologies without CHP capability become effective at abating carbon emissions because PV becomes competitive. CHP-enabled DER technologies, on the other hand, are able to meet heating loads through recovered heat which offsets the need to burn natural gas and the associated carbon emissions. As a result, a larger fraction of the energy is produced on-site and system energy efficiency is increased.

The results of this analysis indicate that policymakers in jurisdictions such as California interested in mitigating carbon emissions should act to remove barriers to CHP-enabled on-site generation, which under some circumstances can be more effective than subsidising capital-intensive "green" technologies, such as PV. While PV is more carbon efficient, it is not operational at night and is not able to offset the direct burning of natural gas for meeting heating loads. By contrast, CHP-enabled DER technologies allow for the co-optimisation of electricity and heating loads, which under some circumstances results in greater reduction of carbon emissions.

Table 2. DER Technology Data

Name	DER Type	Source	Rated Power (kW)	Lifetime (years)	Turnkey Cost (US$/kW)	OM Fixed Cost (US$/kW/year)	OM Variable Cost (US$/kWh)	Lev Cost (US¢/kWh)	Heat Rate (kJ/kWh)	Alpha (kW/kW)	Elemental Carbon Emissions (kg/kWh)
MTL-C-30	MT	SCE[10]	30	12.5	1333	119	0	12.18	12186	2.67	0.17
MTH-C-30	MT	SCE	30	12.5	1333	119	0	12.18	12186	2.51	0.17
PAFC-O-200	PAFC	estimate	200	12.5	3960	0	0.0153	13.68	9480	0	0.13
DE-K-15	Diesel Backup	manu	15	12.5	2257	26.5	0.000033	16.22	18288	0	0.35
DE-K-30	Diesel Backup	manu	30	12.5	1290	26.5	0.000033	10.37	11887	0	0.22
DE-K-60	Diesel Backup	manu	60	12.5	864	26.5	0.000033	9.50	11201	0	0.21
DE-K-105	Diesel Backup	manu	105	12.5	690	26.5	0.000033	8.86	10581	0	0.20
DE-K-200	Diesel Backup	manu	200	12.5	514	26.5	0.000033	9.16	11041	0	0.21
DE-K-350	Diesel Backup	manu	350	12.5	414	26.5	0.000033	8.32	10032	0	0.19
DE-K-500	Diesel Backup	manu	500	12.5	386	26.5	0.000033	8.57	10314	0	0.20
DE-C-7	Diesel Backup	manu	7.5	12.5	627	26.5	0.000033	N/A	10458	0	0.20
DE-C-20	Diesel Backup	manu	20	12.5	1188	26.5	0.000033	11.03	12783	0	0.24
DE-C-40	Diesel Backup	manu	40	12.5	993	26.5	0.000033	9.97	11658	0	0.22
DE-C-100	Diesel Backup	manu	100	12.5	599	26.5	0.000033	8.57	10287	0	0.19
DE-C-200	Diesel Backup	manu	200	12.5	416	26.5	0.000033	8.21	9944	0	0.19
DE-C-300	Diesel Backup	manu	300	12.5	357	26.5	0.000033	8.47	10287	0	0.19
DE-C-500	Diesel Backup	manu	500	12.5	318	26.5	0.000033	7.72	9327	0	0.18
GA-K-25	Gas Backup	manu	25	12.5	1730	26.5	0.000033	13.79	15596	1.72	0.21
GA-K-55	Gas Backup	manu	55	12.5	970	26.5	0.000033	11.32	12997	0.72	0.18
GA-K-100	Gas Backup	manu	100	12.5	833	26.5	0.000033	13.07	15200	1.24	0.21
GA-K-215	Gas Backup	manu	215	12.5	1185	26.5	0.000033	11.59	13157	1.22	0.18
GA-K-500	Gas Backup	manu	500	12.5	936	26.5	0.000033	10.63	12003	0.93	0.16
BOW-50	MT		50	12.5	1500	5	0.015	N/A	11201	0	0.15
BOW-80	MT		80	12.5	1700	7.5	0.015	N/A	10287	0	0.14
PV-5	PV	Jeff Oldman, Real Goods	5	20	8650	14.3	0	55.23	0	0	0.00
PV-20	PV	Jeff Oldman, Real Goods	20	20	7450	14.3	0	47.56	0	0	0.00
PV-50	PV	Jeff Oldman, Real Goods	50	20	6675	12	0	42.62	0	0	0.00
PV-100	PV	Jeff Oldman, Real Goods	100	20	6675	11	0	42.62	0	0	0.00

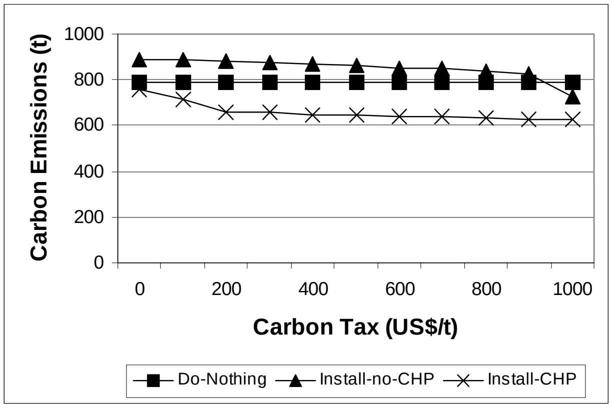

Figure 6. Effect of Carbon Tax on Total Emissions

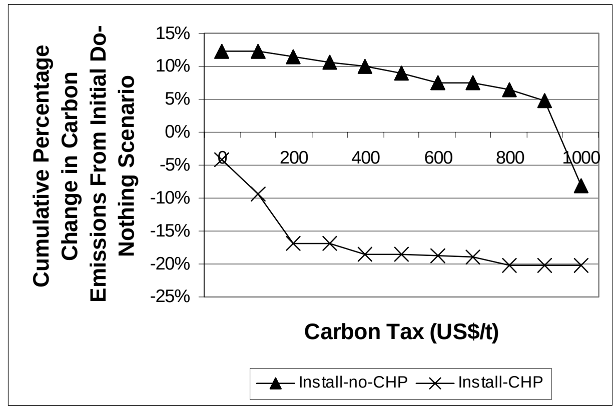

Figure 7. Change in Carbon Emissions from Do-Nothing Scenario

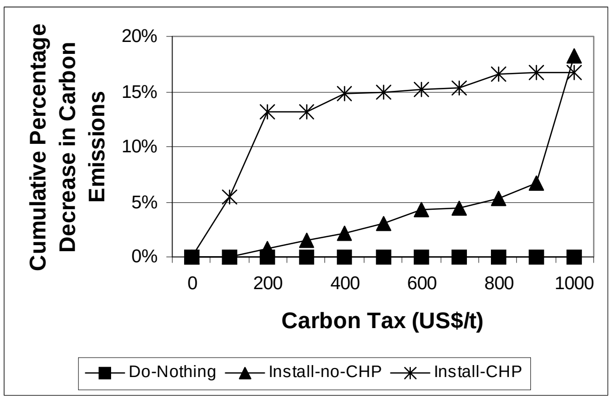

Figure 8. Effect of Carbon Tax on Change in Carbon Emissions

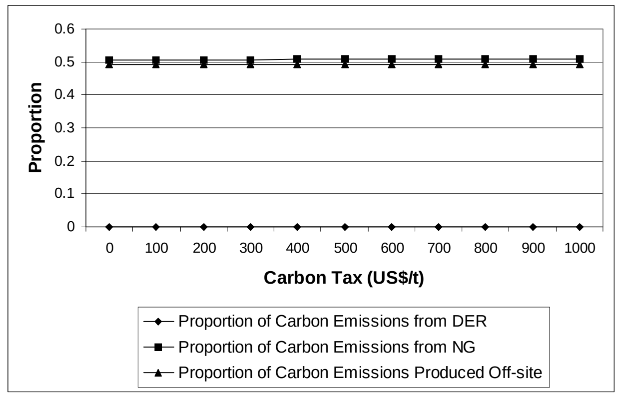

Figure 9. Origin of Carbon Emissions for the Do-Nothing Scenario

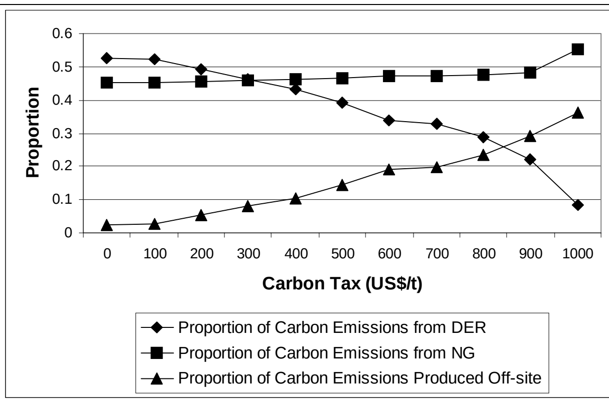

Figure 10. Origin of Carbon Emissions for the Install-no-CHP Scenario

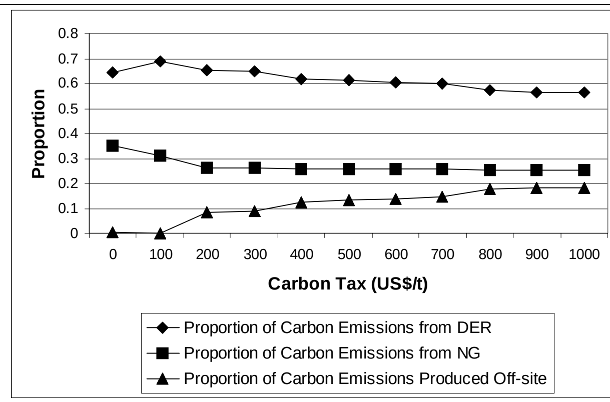

Figure 11. Origin of Carbon Emissions for the Install-CHP Scenario

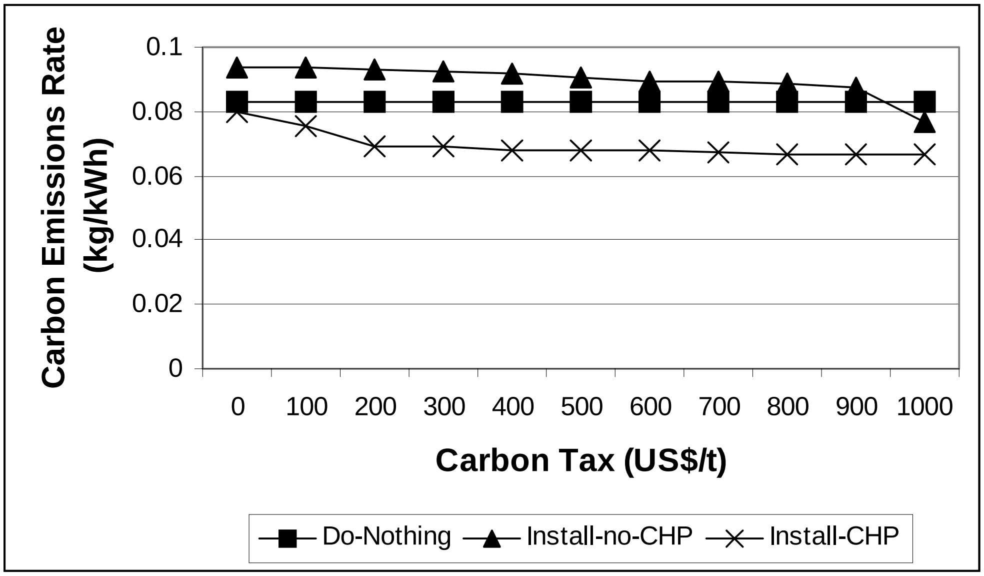

Figure 12. Carbon Emissions Rate By Scenario

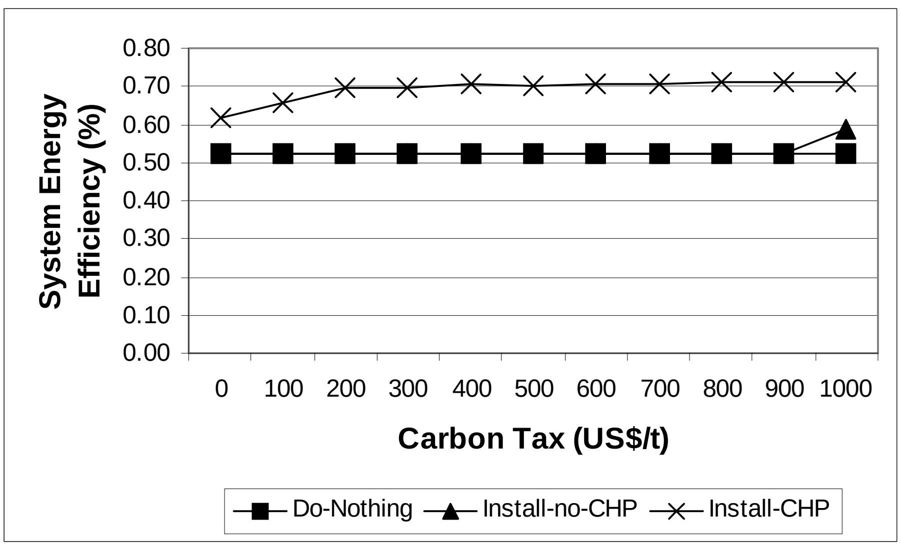

Figure 13. System Energy Efficiency

Bibliography

Lasseter, Robert H., Abbas Akhil, Chris Marnay, John Stephens, Jeff Dagle, Ross Guttromson, A. Sakis Meliopoulos, Robert Yinger, and Joseph H Eto (2002). *White Paper on Integration of Distributed Energy Resources: The CERTS MicroGrid Concept.* Berkeley Lab Report LBNL-50829, Berkeley, CA.

Marnay, Chris, Raquel Blanco, Kristina S. Hamachi, Cornelia P. Kawaan, Julie G. Osborn, and F. Javier Rubio (2000). *Integrated Assessment of Dispersed Energy Resources Deployment*. Berkeley Lab Report LBNL-46082, Berkeley, CA.

Marnay, Chris, J. S. Chard, K. S. Hamachi, Timothy Lipman, M. M. Moezzi, Boubékeur Ouaglal, and A. S. Siddiqui (2001). *Modeling of Customer Adoption of Distributed Energy Resources.* Berkeley Lab Report LBNL-49582, Berkeley, CA.

Piagi, Paolo and Robert H. Lasseter (2001). *Industrial Application of MicroGrids*. Power System Engineering Research Center, University of Wisconsin, Madison, WI.

Price, L., C. Marnay, J. Sathaye, S. Murtishaw, D. Fisher, A. Phadke, and G. Franco (2002). "The California Climate Action Registry: Development of Methodologies for Calculating Greenhouse Gas Emissions from Electricity Generation," in *Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA, 18-23 Aug 2002.

van Sambeek, Emiel (2000). *Distributed Generation in Competitive Electricity Markets*. Center for Energy and Environmental Policy, Working Paper no. 00-S4, Newark, DE.

Weinberg, C.J., J.J. Iannucci, and M.M. Reading (1991). "The Distributed Utility: Technology, Customer, and Public Policy Changes Shaping the Electrical Utility of Tomorrow," *Energy Systems and Policy* 15(4): 307-322.

Acknowledgments

The work described in this report was coordinated by the Consortium for Electric Reliability Technology Solutions, and funded by the Assistant Secretary of Energy Efficiency and Renewable Energy, Office of Power Technologies of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and by the California Energy Commission, Public Interest Energy Research Program, under Work for Others Contract No. BG 99-396 (00). The authors are grateful to other colleagues including Emily S. Bartholomew, Kristina Hamachi LaCommare, Mithra M. Moezzi, Owen Bailey, and Tim Lipman, as well as Consortium for Electric Reliability Technology Solutions (CERTS) partners Abbas A. Akhil, Jeffrey Dagle, Robert H. Lasseter, and Robert Yinger for helpful comments and discussion.

---

[1] GAMS is a proprietary software package that solves optimisation problems. The actual mathematical program is modelled via user-defined algebraic equations. GAMS then compiles them and applies standard solvers to the resulting problem.

[2] All cost data are in 1999 U.S. dollars.

[3] Only the three first variables are decision ones. This fourth one (power purchased from the distribution company) could be expressed as a relationship between the second and third variables. However, for the sake of the model's clarity, it has been maintained.

[4] However, an alternative formulation in which it purchases power at the wholesale imbalance energy market (IEM) price plus a transmission and distribution adder have been used in other work.

[5] Most of the technologies are allowed to generate during all hours of the year, but diesel generators, for example, are allowed to run for only 52 hours per year in accordance with local air quality regulation.

[6] DOE2 is a building energy use and cost analysis software developed by James J. Hirsch & Associates (JJH) in collaboration with Berkeley Lab. See http://www.doe2.com/.

[7] Maisy (Market Analysis and Information System) is an energy industry source of commercial and residential energy and hourly load data. It includes information about building structure, building and end-use energy use, equipment and other variables for over 150,000 customers throughout the U.S. Detailed electricity, natural gas, and oil consumption are also provided. See http://www.maisy.com/.

[8] The volatility is defined by the standard deviation about the value zero:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{x_{i+1}-x_i}{x_i}\right)^2} * 100\%$$

[9] This is calculated as follows:

$$c\_rate = p_e \cdot r_e + p_h \cdot r_h$$

where p_e is the proportion of energy used for electricity, p_h is the proportion of energy used as heat, r_e is the average carbon emissions rate for electricity, and r_h is the average carbon emissions rate for heat.

[10] Southern California Edison utility.