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Afzal S. Siddiqui
University College, Dublin

Chris Marnay, Jennifer L. Edwards, and Ryan Firestone
Environmental Energy
Technologies Division

Srijay Ghosh
Silicon Storage Technologies Inc.

Michael Stadler
Vienna University of Technology

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Afzal S. Siddiqui
Graduate School of Business, Banking, and Finance
University College
Blackrock, Co. Dublin, Ireland

Chris Marnay, Jennifer L. Edwards, and Ryan Firestone
E.O. Lawrence Berkeley National Laboratory
1 Cyclotron Road MS 90R4000
Berkeley CA 94720-8136

Srijay Ghosh
Silicon Storage Technologies Inc.
1171 Sonora Court
Sunnyvale CA 94086

Michael Stadler
Energy Economics Group,
Vienna University of Technology,
Gusshausstrasse 25-29 / E-373-2,
Vienna 1040, Austria

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Abstract

This paper describes the economically optimal adoption and operation of distributed energy resources (DER) by a hypothetical California microgrid 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 microgrid is a semiautonomous grouping of electricity and heat loads interconnected to the existing utility grid (macrogrid) but able to island from it. The microgrid 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 combined heat and power (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 microgrid 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 central station generation in California.

Keywords

Carbon emissions; Combined heat and power; CHP; Distributed energy resources; DER; Distributed Generation; DG; Economic optimisation; Microgrid.

Introduction

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. One possible adjunct to the traditional paradigm is the *microgrid*, a localized network of distributed energy resources (DER) matched to local energy demands (Lasseter 2002). These microgrids 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 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 ready 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 microgrid, which could form a component of a more decentralised power system. A microgrid consists of a localised semi-autonomous grouping of loads, generation, and storage operating under co-ordinated local control, either active or passive. The microgrid is connected to the current power system, or macrogrid, in a manner that allows it to appear to the wider grid as a *good citizen*; that is, the microgrid 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 microgrids will develop in accordance with their independent local incentives. Requiring avoided cost electricity purchases by utilities was the first U.S. step towards abandoning the centralised paradigm, and the ongoing deregulation of central generation represents the second. The emergence of microgrids and other locally controlled systems represents the third, and will be the most technically fundamental to customers. Because microgrids 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 microgrid and the macrogrid occur whenever there are economic benefits for such a transaction, and it is technically and legally feasible.

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 bi-directional 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 microgrids 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, which makes CHP even more attractive when carbon taxes or other emission fees are considered.

Approach of Current Work

This work considers DER adoption as a tool for customer-oriented energy cost minimization. This stands in contrast to much past study of DER, which has tended to consider it an additional option available to utility planners and systems (Weinberg 1991). A recent study evaluated the applicability of the microgrid in organising on-site generation for an industrial application (Piagi 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 (van Sambeek 2000). The starting point here is to minimise the cost of meeting the known electrical and heat loads of a microgrid. 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 microgrid. 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 microgrid's decision to invest in DER technologies?
- Which technologies are more conducive to carbon emissions abatement given the imposition of a carbon tax?

The Berkeley Lab has developed the DER Customer Adoption Model (DER-CAM) for these studies to examine the economics of DER adoption for specific sites and microgrids. DER-CAM models specific sites and selects optimal DER systems to install in parallel to the macrogrid, given utility tariffs, fuel costs, and equipment performance characteristics. This paper provides a mathematical description of DER-CAM and the input data it requires, and then provides results from a carbon tax study.

Mathematical Model

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 (Marnay 2000), the current version additionally incorporates CHP-enabled technologies and carbon taxation (Siddiqui 2003). All versions of the model have been programmed in the commercial optimisation software, GAMS (General Algebraic Modeling System). 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.

Model Description

In its current formulation, the model purchases two fuels, electricity, and natural gas, and supplies four types of end-uses, electricity only (e.g. lighting), heating (i.e. space and domestic hot water), cooling and refrigeration, and natural gas only (i.e. usually just cooking). The model’s objective function is to minimise the cost of supplying the four end uses to a specific microgrid 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 and CHP technology (or combination of technologies) should the microgrid install?
- What is the appropriate level of installed capacity of these technologies that minimises the cost of meeting the microgrid's requirements for energy?
- How should the installed capacity be operated in order to minimise the total bill for meeting the microgrid's four end-use requirements?

The essential inputs to DER-CAM are:

- the microgrid's four load profiles
- default energy tariffs (in this work from the San Diego Gas and Electric Company (SDG&E))
- 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 and from the burning of natural gas for on-site power generation and direct combustion 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) installed and their respective capacities
- hourly operating schedules for installed equipment
- total cost and carbon emissions of supplying the total 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 microgrid can achieve is a reduction in its energy bill.
2. The microgrid is not allowed to generate more electricity than it consumes. On the other hand, if more electricity is consumed than generated, then the microgrid 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 losses and some other operating costs.

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.

Input Parameters

Indices

Name	**Definition**
h	hour {1,2,…,24}
i	technology {the set of technologies selected}
m	month {1,2,…,12}
p	period {on-peak, mid-peak, off-peak} On-peak (hours of the day 12 through 18, inclusive, during summer months, and 18 through 20 during the winter), mid-peak (07 through 11 and 19 through 22 during the summer, and 07 through 17

	and 21 through 22 during the winter), or off-peak (01 through 06 and 23 through 24 during all months)
s	Season {summer, winter} Summer (May through September, inclusive) or winter (the remaining months)
t	day type {weekday, weekend}
u	end use {electricity-only, cooling, space heating, water heating, natural gas only}

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 (in 1999 U.S. dollars)

Name	Description
$RTPower_{s,p}$	Regulated non-coincident 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)
$RTCDCh\arg e_m$	Regulated tariff charge for coincident demand, i.e., 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)
$DCCap$	Capacity of direct-fired natural gas absorption chiller (kW)
$DCPrice$	Turnkey cost of direct-fired natural gas absorption chiller ($)
$S(i)$	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)

Decision Variables

Decision Variables

Name	**Description**
$InvGen_i$	Number of units of technology *i* installed by the customer
DC	Indicator variable for installation of a direct-fired natural gas absorption chiller
$GenL_{i,m,t,h,u}$	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)
$DRLoad_{m,t,h,u}$	Purchased electricity from the distribution company by the customer during hour *h*, type of day *t*, and month *m* for end-use *u* (kW) (this variable is derived from other variables, but listed here for clarity)
$RecHeat_{i,m,t,h,u}$	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)

Problem Formulation

It is assumed that the microgrid acquires the residual electricity that it needs beyond its self-generation from the distribution company (disco) at the regulated tariff. However, an alternative formulation in which it purchases power at the wholesale imbalance energy market (IEM) price plus a transmission and distribution adder has been used in other work. The mathematical formulation of the disco purchase problem follows:

$$\min_{\substack{InvGen_i\\ GenL_{i,m,t,h,u}\\ GasP_{m,t,h,u}\\ RecHeat_{i,m,t,h,u}\\ DC}} \quad \sum_m RTFCharge\cdot\max\left(\sum_{u\in\{electric-only,cooling\}} DRLoad_{m,t,h,u}\right)+\sum_m RTCCharge$$

$$+\sum_s\sum_{m\in s}\sum_p RTPower_{s,p}\cdot\max\left(\sum_{u\in\{electric-only,cooling\}} DRLoad_{m,(t,h)\in p,u}\right)$$

$$\begin{aligned}
&+\sum_{m}\sum_{u\in\{electric-only,cooling\}} RTCDCharge_{m}\cdot DRLoad_{m,t(m),h(m),u} + DCPrice\cdot DC\\
&+\sum_{m}\sum_{t}\sum_{h}\sum_{u} DRLoad_{m,t,h,u}\cdot\left(RTEnergy_{m,t,h}+CTax\cdot MktCRate\right)\\
&+\sum_{i}\sum_{m}\sum_{t}\sum_{h}\sum_{u} GenL_{i,m,t,h,u}\cdot DERCostkWh_{i} + \sum_{i}\sum_{m}\sum_{t}\sum_{h}\sum_{u} GenL_{i,m,t,h,u}\cdot DEROMvar_{i}\\
&+\sum_{i}\sum_{m}\sum_{t}\sum_{h} GenL_{i,m,t,h}\cdot CTax\cdot CRate_{i}\\
&+\sum_{i} InvGen_{i}\cdot DERmaxp_{i}\cdot\left(DERcapcost_{i}\cdot AnnuityF_{i}+DEROMfix_{i}\right)+\sum_{m} NGBSF_{m}\\
&+\sum_{m}\sum_{t}\sum_{h}\sum_{u} GasP_{m,t,h,u}\cdot NGHR\cdot\left(NatGasPrice_{m,t,h}+CTax\cdot NGCRate\right)
\end{aligned}\tag{1}$$

Subject to:

$$Cload_{m,t,h,u} = \sum_{i} GenL_{i,m,t,h,u} + DRLoad_{m,t,h,u} + \beta_{u}\cdot GasP_{m,t,h,u} + \sum_{i}\left(\gamma_{i,u}\cdot RecHeat_{i,m,t,h,u}\right)\forall\, m,t,h,u \tag{2}$$

$$\sum_{u} GenL_{i,m,t,h,u} \le InvGen_{i}\cdot DER\max p_{i}\quad \forall\, i,m,t,h \tag{3}$$

$$AnnuityF_{i} = \frac{IntRate}{\left(1-\frac{1}{\left(1+IntRate\right)^{DERlifetime_{i}}}\right)}\forall\, i \tag{4}$$

$$\sum_{u} GenL_{j,m,t,h,u} \le InvGen_{j}\cdot DER\max p_{j}\cdot Solar_{m,h}\quad \forall\, m,t,h\ \ if\ \ j\in\{PV\} \tag{5}$$

$$\sum_{m}\sum_{t}\sum_{h}\sum_{u} GenL_{i,m,t,h,u} \le InvGen_{i}\cdot DER\max p_{i}\cdot DERhours_{i}\ \ \forall\, i \tag{6}$$

$$\sum_{u} RecHeat_{i,m,t,h,u} \le \alpha_{i}\cdot\sum_{u} GenL_{i,m,t,h,u}\ \forall\, i,m,t,h \tag{7}$$

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

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

$$GasP_{m,t,h,u} \le \mathrm{DCCap}\cdot\mathrm{DC}\quad \forall\, m,t,h\quad if\quad u\in\{cooling\} \tag{10}$$

$$DRLoad_{m,t,h,u} = 0\quad \forall\, m,t,h\quad if\quad u\in\{space-heating, water-heating, natural-gas-only\} \tag{11}$$

Equation (1) is the objective function that states that the microgrid 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 microgrid 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. Local air quality regulations may restrict the yearly operating hours of certain technology types.
- 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 (11) are boundary conditions that prevent electricity from being used directly to meet heating loads
- equation (10) prevents direct burning of natural gas to meet the cooling load if no absorption chiller for this purpose is purchased

Input Data

Customer Loads

DER-CAM is run for a hypothetical microgrid over the test year of 1999. The microgrid is composed of several typical southern California commercial electricity customers acting as one. **Table 1** details this composition. Collectively, the microgrid derives some advantage from the fact that when the customers pool their loads, the resulting load is flatter than most individuals' loads, and therefore, less exposed to tariff demand charges. In other words, the load factors for the majority of sites are less than the aggregated microgrid load factor (**Table 1**). The microgrid as a whole cannot be peakier than its peakiest individual, and in general will tend to be less peaky than a typical individual customer. However, it is possible the certain customers individually would be less peaky than the microgrid. This paper does not isolate the economic savings from peakiness reduction, nor consider equitable schemes for distributing these savings amongst microgrid members.

January and July weekday electricity and natural gas loads prior to DER are presented in Figure 1 through Figure 4. Note that with DER electric loads can be met by natural gas and that with CHP, cooling and heating loads can be met by recovered heat. The individual customer electricity and thermal loads for California in the year 1999 were extracted from a variety of sources, including enduse metered loads from a distribution utility monitoring program, the building energy simulation software DOE2, and the commercially available Market Analysis and Information System (MAISY) data base (Marnay 2001).

Utility Tariff and Carbon Emissions

Parameters of the SDG&E tariff used in this study are summarised in Table 2. Additionally, there is a monthly customer charge of US$43.50. The time period definitions are shown in *Indices* table of the Mathematical Model section. An unusual feature of the tariff is the dual demand (peak power) charges, one (*non-coincident charge*) at the time of the customer's individual peak and a second (*coincident demand*) at the time of the overall system peak.

Carbon taxes of zero to $1000 per metric ton of carbon are considered, in increments of $100/t.

Were carbon taxes implemented in the United States, they would probably lie in the range of zero to $100/t. However, the California macrogrid has lower carbon emission rates than are typical for the United States, due to significant use of electricity generated from natural gas, nuclear, hydroelectric, and renewable sources. Carbon emissions rates from distributed generation are comparable with those from the California macrogrid, therefore carbon taxes in the range of zero to $100/t have little effect on DER adoption, as will be seen in the results. However, larger carbon taxes do affect DER adoption and are used in this study to illustrate these effects.

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 (Price 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 higher, and an analysis in which the utility charged a marginal rather than average carbon tax on delivered electricity would significantly benefit DER.

DER Technologies

The generating technologies available to the microgrid are microturbines manufactured by Capstone, phosphoric acid fuel cells made by UTC Power, Katolight natural gas reciprocating generators, and photo-voltaic (PV) cells. Diesel engines were not considered in this study because regional air quality restrictions prevent their use for prime power generation. In such situations, diesel engines provide value as a back-up power source during outages, but do not provide energy cost savings. DER-CAM has the capability to consider diesel engines and limits (when applicable) on their annual operating hours.

For each of the considered technologies, the nameplate capacity (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 (natural gas or solar radiation) are provided (see Table 3 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 the Mathematical Model section) α_i and $\gamma_{i,u}$ describe the recoverable waste heat and heat exchanger efficiency, respectively: α_i is the ratio of recoverable heat (kW) to electricity generated (kW) by technology *i*, and ranges from 0.72 and 2.67 for the technologies in Table 3; $\gamma_{i,u}$ is assumed to be 0.8 for conversions of waste heat to useful heat and 0.11 for conversions of waste heat to cooling; β_u is the efficiency of converting fuel energy into end-uses and is assumed to be 0.8 for fuel to heating conversion and 0.22 for fuel to cooling conversions. The lower value of $\gamma_{i,u}$ and β_u for cooling accounts for the fact that indirect fired absorption cooling is inefficient compared to compressor cooling. Roughly seven times more energy (in the form of low temperature waste-heat) is required to provide the same amount of cooling as an electric compressor, and direct fired absorption chillers require roughly four times more input energy. Note however, that absorption cooling, either direct fired or by waste heat, can still be attractive economically to a microgrid because of the high cost on-peak power used by cooling, especially when demand charges are in place.

Fuel Data

The other data needed to run DER-CAM are fuel prices, carbon emissions rates, and the carbon tax rate. 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, with a low volatility of 8.8%. The volatility is defined by the standard deviation about the value zero:

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

Results

In this section, the effects of carbon taxation on DER adoption, particularly with CHP, and the resulting 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 microgrid 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 in the case of a high carbon tax, so the microgrid switches to using the slightly less polluting macrogrid to meet its electricity needs. This can be readily seen by comparison of the carbon emission rates of DER technologies shown in Table 3 with the assumed macrogrid emission rate of 0.13 kg/kWh. 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. With CHP, however, the microgrid is able to use recovered heat to meet its heating loads, thereby emitting very little carbon in meeting these loads. Consequently, DER technologies with carbon emissions rates of 0.17 kg/kWh (such as the microturbines in Table 3) 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, more than 90% of the microgrid's electricity demand is met via DER for the entire range of carbon taxes (Figure 7). However, for the install-no-CHP case, this percentage decreases with increasing carbon taxes to less than 50% for carbon taxes of $900/t and $1000/t (Figure 7). The energy efficiency of systems with DER with CHP is greater than without CHP, implying that fewer resources are needed with CHP than without to satisfy the same level of energy consumption. Note finally that, with or without CHP, on-site generation was competitive with grid purchased power in southern California of 1999, and over a wide range of carbon tax rates.

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 5, 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$900/t. For a large range of carbon tax levels in the "install-no-CHP" scenario, the microgrid installs one 500 kW and five 55 kW natural gas-fired backup engines, which have relatively low turnkey costs and rates of carbon emissions (see Figure 6). However, they are still more polluting than the macrogrid. Therefore, the microgrid self-provides a declining percentage of its own electricity needs as the carbon tax increases (see Figure 7). In other words, the on-site generators are used less frequently as the tax is increased. They are not abandoned entirely probably to avoid the high demand charges.

Similarly, in the "install-CHP" scenario, the level of adopted capacity also stays constant, with one unit of the 500 kW CHP-enabled natural gas engines and a few 55 kW natural gas engines frequently installed (see Figure 8). For carbon taxes of US$700/t and higher, cooling-enabled technologies become favoured. The difference from the non-CHP installation scenario is that the microgrid still finds it economical to meet most of its electricity needs on-site even as the carbon tax increases (see Figure 7). Indeed, although the increasing carbon tax makes on-site electricity production less attractive than macrogrid generation, the microgrid 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 9).

Effect of Carbon Tax on Emissions

In the “install-no-CHP” scenario, carbon emissions decrease slightly as the carbon tax increases (see Figure 10). 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 microgrid relies more on the macrogrid until carbon taxes approach US$900/t, at which point it installs PV cells. Nevertheless, even the adoption of high capital cost PV technologies do not decrease carbon emissions from the "do-nothing" level as CHP does (see Figure 11). 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 widespread. Indeed, for even a relatively “low” carbon tax of US$100/t, carbon emissions are reduced by over 3% from their initial level (see Figure 12). Even without a carbon tax, the use of CHP-enabled DER equipment permits the microgrid to attain lower level of carbon emissions relative to the "do-nothing" scenario (see Figure 11). This illustrates the potential for reducing carbon emissions at low levels of carbon taxation via CHP-enabled DER generation. Thus, from a policy perspective, carbon emissions abatement is more effective when CHP-enabled DER equipment is installed than when CHP is not present in DER systems. The use of CHP itself is facilitated by the microgrid concept which allows loads to be pooled and recovered heat to be utilised where it is most needed.

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 16). Policymakers trying to achieve carbon emissions abatement should consider the beneficial impact of cost effective CHP-enabled DER generation and promote it, along with other carbon free technologies such as PV.

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 17) coincides with the increasing amounts of energy self-provided via CHP (see Figure 7).

For the "install-no-CHP" scenario, system energy efficiency stays constant for most values of the carbon tax because only the natural gas-fired generators are utilised. Since their efficiencies are 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.

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 microgrid composed of commercial enterprises. The microgrid's objective is to minimise the cost of meeting its energy load through either local utility purchases or on-site generation. Significant features of this model include customer-perspective approach and the joint optimisation of heating and electric loads. The resulting optimisation problem is solved using

GAMS, thus quantifying the economics of DER adoption for this microgrid over a large range of carbon taxation. 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 microgrid.

In California, implementing DER technologies that are not CHP-enabled is no more effective at reducing carbon emissions than using the macrogrid because these DER technologies have similar energy efficiencies and carbon emissions rates. 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, when carbon taxes inflate the efficiency differential between on-site and utility power generation. Under the assumptions of this work, only when the carbon tax reaches extreme 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. Even though cooling using waste heat is inefficient compared to compressor cooling, its attractive economics and low relative carbon emissions also make it an attractive technology.

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 power is carbon free, it is not operational at night and is not able to offset the direct burning of natural gas for heating. By contrast, CHP-enabled DER technologies allow for the co-optimisation of electricity and heating loads, and can also displace electricity generated for cooling by waste heat, which under some circumstances results in greater reduction of carbon emissions.

Acknowledgments

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Table 1. Energy Characteristics of Microgrid’s Individual Members

Type	# of Sites	Total Annual Electricity (MWh)	Peak Load (kW)	Peak Hour	Load Factor
Residential	45	242	50	December Weekend 17:00	56%
Office	6	234	72	July Weekday 13:00	32%
Medical Office	1	242	87	July Weekday 13:00	27%
Retail 1	4	647	172	July Weekend 15:00	43%
Retail 2	2	111	26	July Weekend 15:00	48%
Retail 3	2	256	54	October Weekday 18:00	53%
Retail 4	4	141	37	July Weekend 15:00	43%
Restaurant	3	366	69	July Weekend 19:00	60%
Hospital	1	2449	406	January Weekend 8:00	69%
Laundromat	1	67	18	June Weekday 18:00	42%
Total	69	4755	886*	July Weekday 15:00	60%

*This is the coincident peak for the aggregation of sites and is therfore less than the sum of the sites' individual peaks because they occur at different times.

Table 2. SDG&E Tariff Information for 1999

Tariff Type	Season	Load Period	Non-coincident Demand 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

Table 3. DER Technology Data

Name	**DER Type**	**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-30	microturbine, low pressure	30	12.5	1333	119	0	12.18	12186	2.67	0.17
MTH-30	microturbine, high pressure	30	12.5	1333	119	0	12.18	12186	2.51	0.17
PAFC-200	fuel cell	200	12.5	3960	0	0.0153	13.68	9480	0	0.13
GA-25	natural gas engine	25	12.5	1730	26.5	0.000033	13.79	15596	1.72	0.21
GA-55	natural gas engine	55	12.5	970	26.5	0.000033	11.32	12997	0.72	0.18
GA-100	natural gas engine	100	12.5	833	26.5	0.000033	13.07	15200	1.24	0.21
GA-215	natural gas engine	215	12.5	1185	26.5	0.000033	11.59	13157	1.22	0.18
GA-500	natural gas engine	500	12.5	936	26.5	0.000033	10.63	12003	0.93	0.16
MT-50	microturbine	50	12.5	1500	5	0.015	N/A	11201	0	0.15
MT-80	microturbine	80	12.5	1700	7.5	0.015	N/A	10287	0	0.14
PV-5	photovoltaics	5	20	8650	14.3	0	55.23	0	0	0
PV-20	photovoltaics	20	20	7450	14.3	0	47.56	0	0	0
PV-50	photovoltaics	50	20	6675	12	0	42.62	0	0	0
PV-100	photovoltaics	100	20	6675	11	0	42.62	0	0	0

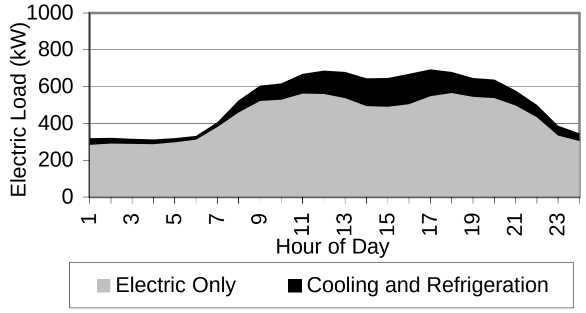

Figure 1. Microgrid Do-Nothing Electric Loads for January Weekday

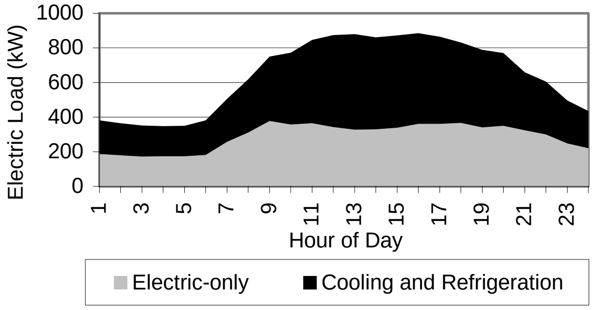

Figure 2. Microgrid Do-Nothing Electric Loads for July Weekday

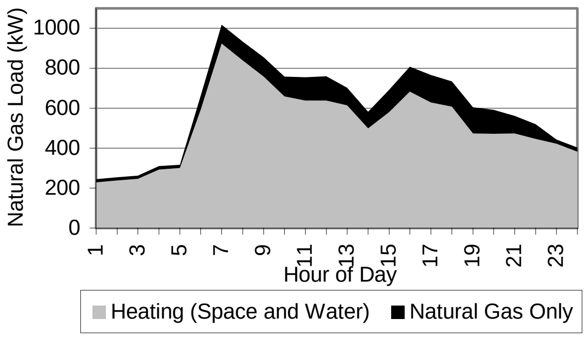

Figure 3. Microgrid Do-Nothing Natural Gas Loads for January Weekday

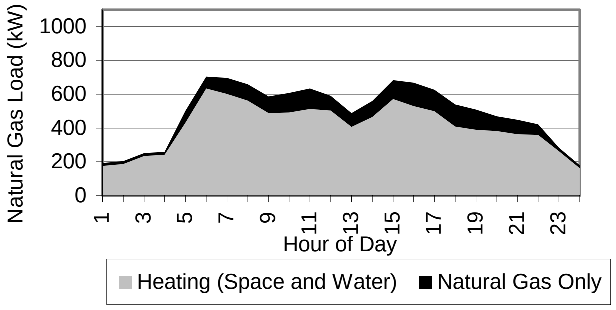

Figure 4. Microgrid Do-Nothing Natural Gas Loads for July Weekday

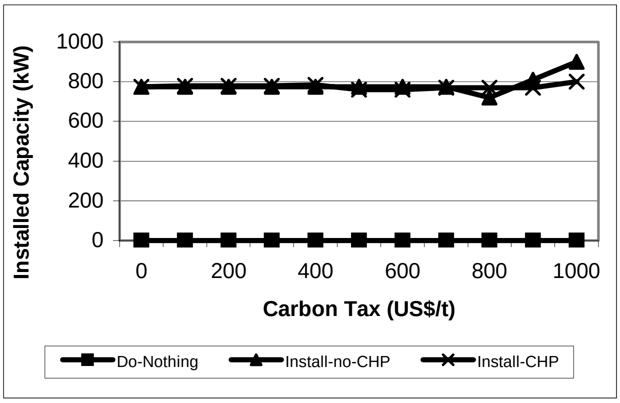

Figure 5. Effect of Carbon Tax on Installed Capacity

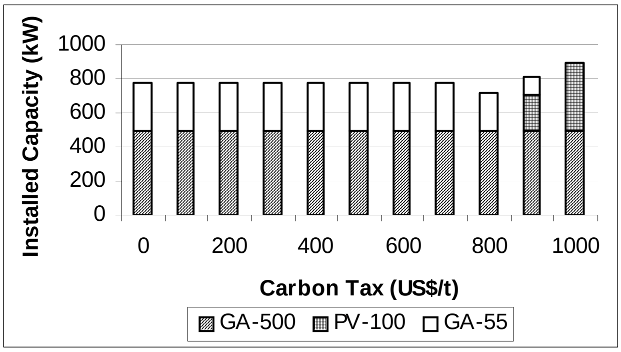

Figure 6. Installed Capacity for Install-no-CHP Scenario

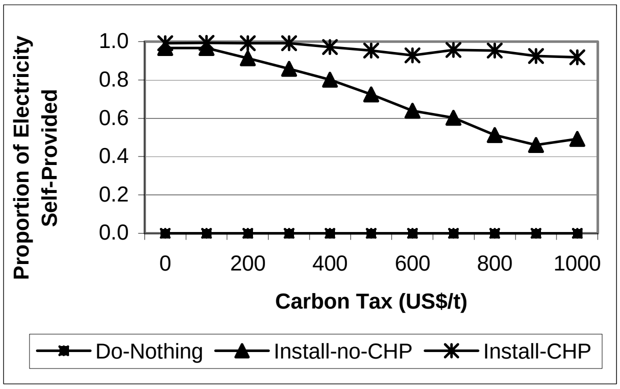

Figure 7. Effect of Carbon Tax on Self-Provision of Electricity

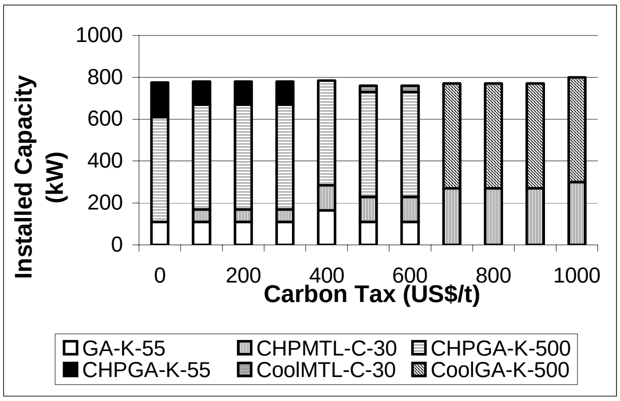

Figure 8. Installed Capacity for Install-CHP Scenario

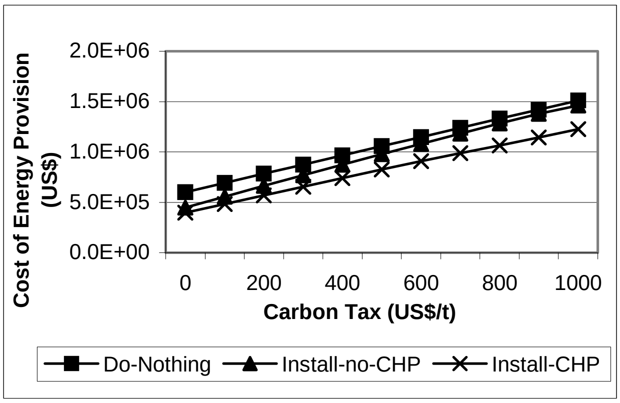

Figure 9. Effect of Carbon Tax on Total Cost

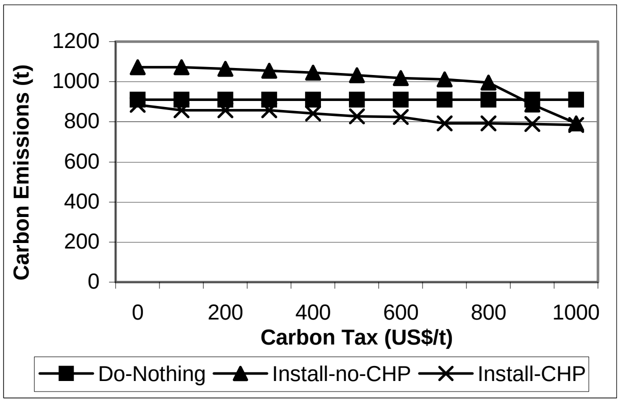

Figure 10. Effect of Carbon Tax on Total Emissions

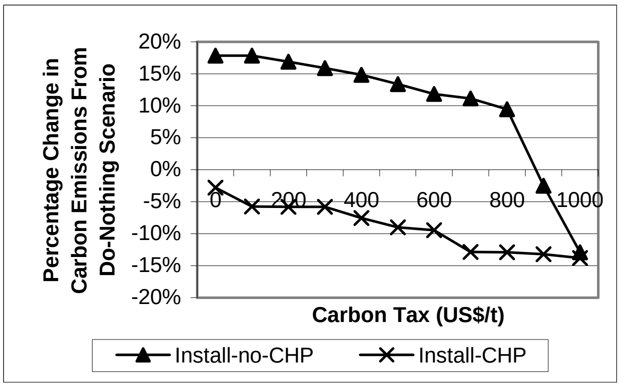

Figure 11. Change in Carbon Emissions from Do-Nothing Scenario

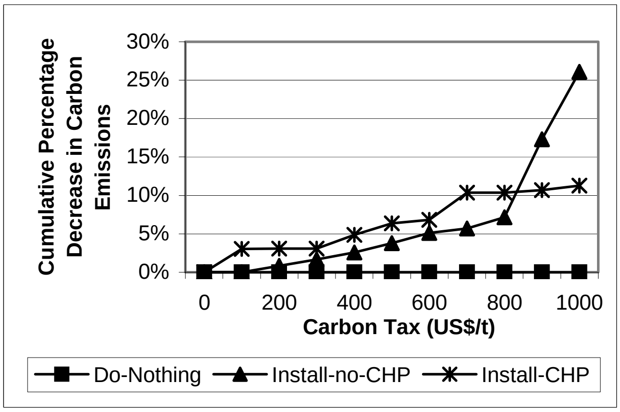

Figure 12. Effect of Carbon Tax on Change in Carbon **Emissions**

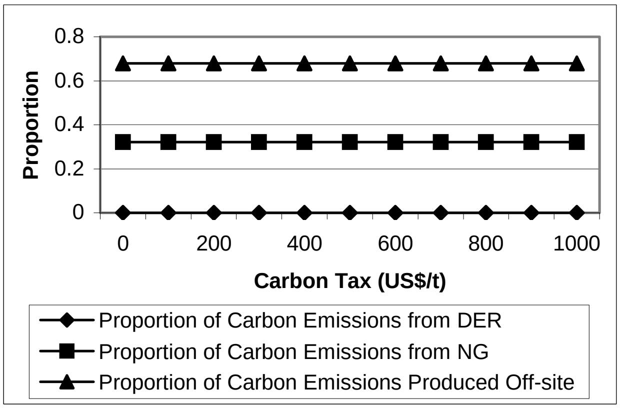

Figure 13. Origin of Carbon Emissions for the Do-Nothing Scenario

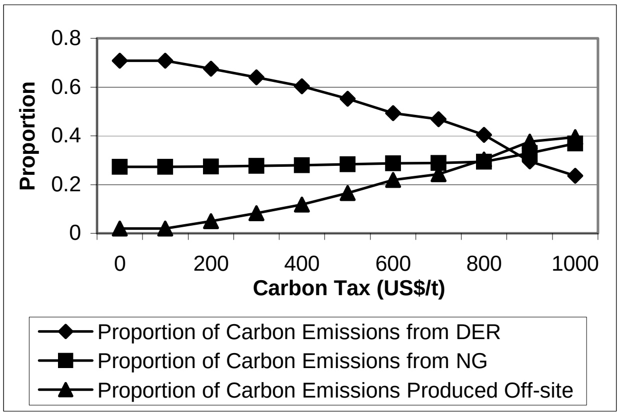

Figure 14. Origin of Carbon Emissions for the Install-no-CHP Scenario

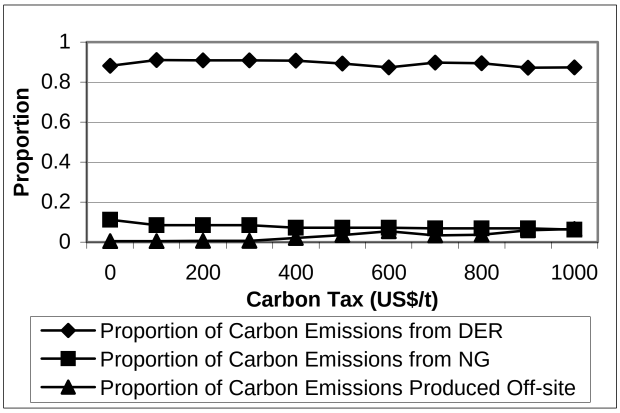

Figure 15. Origin of Carbon Emissions for the Install-CHP Scenario

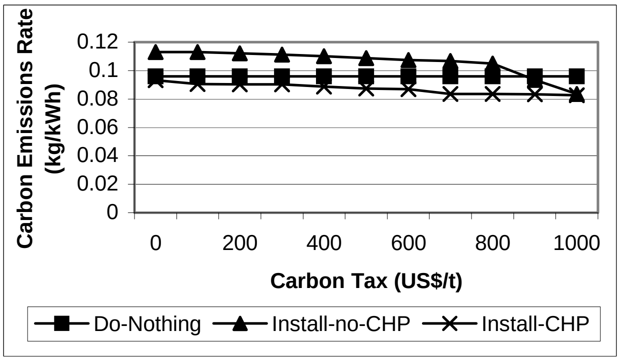

Figure 16. Carbon Emissions Rate By Scenario

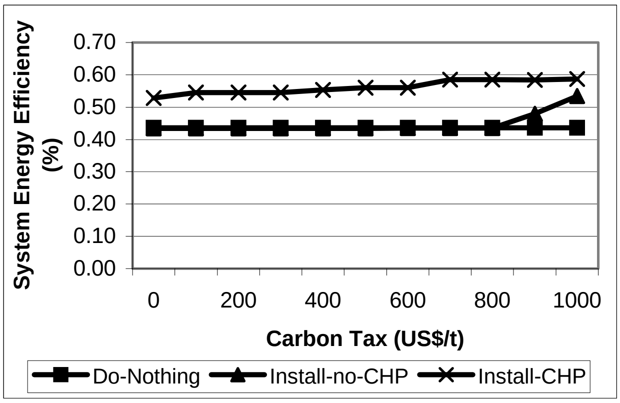

Figure 17. System Energy Efficiency

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