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# The Implications of Carbon Taxation on Microgrid Adoption of Small-Scale On-Site Power Generation Using a Multi-Criteria Approach[1]

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# Table of Contents

Table of Contents ..... ii

List of Figures and Tables ..... iii

Abstract ..... iv

1. Introduction ..... 1

1.1 Microgrid Concept ..... 1
1.2 Approach of Current Work ..... 2

2. Mathematical Model ..... 3

2.1 Introduction ..... 3
2.2 Model Description ..... 3
2.3 General Algebraic Modelling System (GAMS) ..... 4
2.4 Mathematical Formulation ..... 4

3. Customer Description and Input Data ..... 8

3.1 Load Shape Data ..... 8
3.2 SDG&E Tariff and IEM Prices ..... 9
3.3 Generating Technology Data ..... 11
3.4 Fuel Data ..... 12
3.5 Carbon Costs ..... 12

4. Results ..... 13

4.1 Effect of Carbon Tax on Generation ..... 13
4.2 Effect of Carbon Tax on Emissions ..... 17

5. Conclusions ..... 19

Bibliography ..... 20

## List of Figures and Tables

Figure 1. Office Monthly Peak Load ..... 9
Figure 2. California Independent System Operator (CAISO) IEM Price Summary for 2000.. 10
Figure 3. Solar Insolation as a Fraction of Historical Peak Value Received in the Southern California Test Area ..... 12
Figure 4. Installed DER Capacity ..... 15
Figure 5. Installed DER Technologies for the Base Case ..... 15
Figure 6. Installed DER Technologies for the Disco SDG&E Tariff Case ..... 15
Figure 7. Installed DER Technologies for the 25% Subsidy Case ..... 15
Figure 8. Installed DER Technologies for the 50% Subsidy Case ..... 15
Figure 9. Effect of Carbon Tax on Energy Generation and Costs for the Base Case ..... 16
Figure 10. Effect of Carbon Tax on Energy Generation and Costs for the Disco SDG&E Tariff Case ..... 16
Figure 11. Effect of Carbon Tax on Energy Generation and Costs for the 25% Subsidy Case 16
Figure 12. Effect of Carbon Tax on Energy Generation and Costs for the 50% Subsidy Case 16
Figure 13. Percentage Cost Increase Due to Carbon Tax ..... 17
Figure 14. Cumulative Percentage Decrease in Carbon Emissions ..... 18
Figure 15. Carbon Emissions Comparison for the Base Case ..... 19
Figure 16. Carbon Emissions Comparison for the Disco SDG&E Tariff Case ..... 19
Figure 17. Carbon Emissions Comparison for the 25% Subsidy Case ..... 19
Figure 18. Carbon Emissions Comparison for the 50% Subsidy Case ..... 19

Table 1. μGrid Summary ..... 9
Table 2. SDG&E AL-TOU (General Service Time-of-Use) Tariff Information ..... 10
Table 3. SDG&E AL-TOU Fixed Customer Charges ..... 10
Table 4. DER Technology Characteristics ..... 11
Table 5. Fuel Data ..... 12
Table 6. Operating Scenarios for Purchasing Electricity ..... 13
Table 7. Percentage of Carbon Emissions from Macrogrid ..... 16

## Abstract

The electricity supply system is undergoing major regulatory and technological change with significant implications for the way in which the sector will operate (including its patterns of carbon emissions) and for the policies required to ensure socially and environmentally desirable outcomes. One such change stems from the rapid emergence of viable small-scale (i.e., smaller than 500 kW) generators that are potentially competitive with grid-delivered electricity, especially in combined heat and power configurations. Such distributed energy resources (DER) may be grouped together with loads in *microgrids* (μGrids). These clusters could operate semi-autonomously from the established power system, or *macrogrid*, matching power quality and reliability more closely to local end-use requirements. The impact of a carbon tax on DER adoption by the μgrid and resulting carbon emissions is assessed here, using a combined cost approach. In general, we find that increases in the carbon tax stimulate DER adoption, with the added DER capacity being overwhelmingly from "green," or environmentally benign technologies. Furthermore, more carbon emissions abatement is possible at lower levels of carbon tax if "green" DER technologies are granted subsidies towards their turnkey costs. However, these results are sensitive to the regulatory environment, however. For example, carbon emissions abatement is greater under the tariff scenario than in one that allows the μgrid to purchase electricity from the open market.

# 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 organized as monolithic centralized 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. μGrids will operate according to their protocols and standards, will match power quality and reliability to individual load requirements, and will exploit efficiency improving technologies, especially those using 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, including renewable, thermal, and chemical, will improve significantly in terms of cost and performance,
2. Setting constraints, environmental concerns, fossil fuel costs and availability, and other limits will impede continued expansion of the existing electricity supply infrastructure,
3. The potential for application of small-scale CHP technologies will tilt power generation economics in favor 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 intensify, and
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.

Together, these forces will make generation of electricity from resources based close to end uses competitive with central station generation for a significant number of customers.

This research is built upon the fundamental concept of the μGrid, which could contribute to a more decentralized power system. A μGrid consists of a localized semi-autonomous grouping of loads, generation, and storage operating under a form of co-ordinated local control, either active or passive. The μGrid 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 μGrid performs as a legitimate entity under grid rules, e.g., as what we currently consider a normal electricity *customer* or *generating unit*.

The μGrid would most likely exist on a small, dense group of contiguous geographic sites that exchange electrical energy through a low voltage (e.g., 480 V) network and heat through exchange of working fluids. In warmer climates, the commercial and industrial sector heat loads may well include absorption cooling. The generators, loads, and storage within the cluster are placed and co-ordinated to minimize the joint cost of serving internal electricity and heat demand, given prevailing market conditions, while operating safely and maintaining power balance and quality. This pattern of power generation and consumption is distinctly different from existing power systems in that the energy sources and sinks within the cluster can be maintained in a balanced and stable state without active external control or support, possibly within a passively controlled *plug and play* system.

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 centralized authority. μGrids will develop in accordance with their independent incentives. The ongoing deregulation of central generation represents the first step towards abandoning the centralized paradigm, while the emergence of μGrids represents the second. 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. Co-ordinated global planning will, thus, be influenced by the emergence of this new paradigm.[4]

The emergence of the μGrid partially stratifies the current strictly hierarchical centralized control of the power system into at least two layers. The upper layer macrogrid is the one with which current power engineers are familiar, i.e., large central station generation interconnected to the high voltage meshed power grid. A centralized control center dispatches a limited set of large assets in keeping with contracts established between electricity and ancillary services buyers and sellers, while maintaining the energy balance and power quality, protecting the system, and ensuring reliability. At the same time, where they operate, a lower layer of μGrids jointly controls local generation, load, and storage to meet end use requirements for energy and power quality and reliability (PQR). Exchange of power between the μGrid and the macrogrid can be made whenever there are economic benefits for such an exchange, i.e., in order to minimize the overall cost of meeting the μGrid's energy service requirements.

Control of the generating and transmission assets of the macrogrid is governed by extremely precise technical standards that are uniform on regional scales, and the key parameters of the grid, such as frequency and voltage, are maintained strictly within tight tolerances. This control paradigm ensures overall stability and safety and attempts to guarantee that power and ancillary service delivery between sellers and buyers is as efficient and reliable as reasonably possible. However, it should be recognized that uniform standards of PQR are unlikely to match well with the optimal requirements of individual end uses that are highly heterogeneous, e.g., with server farms at one end of the reliability requirement spectrum and irrigation water pumps at the other. μGrids move the PQR choice closer to the end uses and permit it to match the end use's needs more effectively. Therefore, μGrids can improve the overall efficiency of electricity delivery at the point of end use; and as μGrids become more prevalent, the PQR standards of the macrogrid can ultimately be matched to the purpose of bulk power delivery.

## 1.2 Approach of Current Work

The approach taken in this work is strictly customer oriented. This stands in contrast to past study of DER, which has tended to consider DER as an additional option available to utility planners and systems (Weinberg, Iannucci, and Reading 1993). A recent study evaluated the applicability of the μGrid in organizing onsite generation for industrial application (Piagi and Lasseter 2001). Further, 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 is to minimize the cost of meeting the known electrical load of a μGrid. Techniques for optimally solving this problem have been developed over many years for planning and operating utility scale systems. Since the customer-scale problem is, at the level of analysis of this paper, essentially no different from the utility-scale problem,

[4] It is estimated that DER may supply 20-30% of the loads.

established methods can be readily adapted. In future work, some of the specific problems related to μGrids will be incorporated, such as the central role of CHP and load control of μGrid PQR. However, the approach in this work is purely from a traditional power systems economics perspective. While the patterns of potential customer adoption and generation are interesting in themselves, this model is a means for answering two specific questions:

1. How does the presence of a carbon tax stimulate the μGrid to install more environmentally benign technologies?
2. Which regulatory frameworks are more conducive to carbon emissions abatement via imposition of a carbon tax?

## 2. Mathematical Model

### 2.1 Introduction

In this section, the second version of the DER Customer Adoption Model (DER-CAM) with a carbon tax capability is presented. This version of the model has been programmed in GAMS (General Algebraic Modeling System)[5]. This section contains a description of GAMS and a description of the present version of the model's mathematical formulation. 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. Taking account of the possible benefits of locally adjusting, as well as exploiting, reliability CHP applications are necessary technical enhancements to DER-CAM.

### 2.2 Model Description

In a previous report, the first spreadsheet version of the Customer Adoption Model was described and implemented (Marnay *et al.* 2000). A follow-up report used GAMS to solve the Customer Adoption Model (Marnay *et al.* (2001). The current work extends that model to account for carbon taxes. The model's objective function, which has not essentially changed, is to minimize the cost of supplying electricity to a specific μGrid by optimizing the distributed generation of part or the whole 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 minimizes the cost of meeting the μGrid's electricity requirement?
- How should the installed capacity be operated in order to minimize the total bill for meeting the μGrid's electricity load?

It is then possible to determine the technologies and capacity the μGrid is likely to install, to predict when the μGrid will be self-generating and/or transacting with the grid, and to determine whether it is worthwhile for the μGrid to disconnect entirely from the macrogrid.

The essential inputs to DER-CAM are:

- The μGrid's electricity load profile.

[5] GAMS is a proprietary software product used for high-level modeling of mathematical programming problems. It is owned by the GAMS Development Corporation (http://www.gams.com) and is licensed to Berkeley Lab.

- Either the default tariff (assumed to be from San Diego Gas and Electric Company, or SDG&E) or the California independent system operator (CAISO) imbalance energy market (IEM) price at all hours of the test year (2000), which are alternative electricity purchase options for the μGrid.
- Capital, operating and maintenance (O&M), and fuel costs of the various available DER technologies, together with the interest rate on customer investment.
- Basic physical characteristics of alternative generating technologies.
- Rate of carbon emissions from both the macrogrid and DER technologies.
- Carbon tax rates.

Outputs to be determined by the optimization are:
- Technology (or combination of technologies) to be installed.
- Capacity of each technology to be installed.
- When and how much of the capacity installed will be running during the test year.
- Total cost of supplying the electricity requirement.
- Whether or not the customer should, from an economic point of view, remain connected to the grid.
- The impact of carbon taxes on the installation and operation of DER technologies, both in terms of overall capacity and the choice of equipment.

The important assumptions are:
- Customer decisions are taken based only on direct economic criteria. In other words, the only benefit that the μGrid can achieve is a reduction in its electricity bill.
- 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 either at the default tariff rate or at the IEM price. No other market opportunities, such as sale of ancillary services or bilateral contracts, are considered.
- Manufacturer claims for equipment price and performance are accepted without question, nor is any deterioration in output or efficiency during the lifetime of the equipment considered. Furthermore, installation, permitting and other costs are not considered in the capital cost of equipment and start-up and other operating costs are not included.
- CHP benefits, 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. This underestimates the benefit of DER to many potential μGrids.

## 2.3 General Algebraic Modeling System (GAMS)

GAMS is a proprietary software package that solves optimization problems. The actual mathematical program is modeled via user-defined algebraic equations. GAMS then compiles them and uses standard solvers to solve the resulting problem. The foremost advantage of using GAMS is that it allows researchers to build models that can be quickly altered to address different situations or perform sensitivity analysis.

## 2.4 Mathematical Formulation

This section describes intuitively the core mathematical problem solved by DER-CAM. It is structured into three main parts. First, the input parameters are listed. Second, the decision

variables are defined. Third, the optimization problem is described for two possible tariff options.

### 2.4.1 Variables and Parameters Definition

#### 2.4.1.1 *Parameters (input information)*

*Time Scale Definition*

| Name | Definition |
|---|---|
| *Day Type* | peak (the average of the three days of the month with the biggest load), week (the remaining work days), or weekend |
| *Season* | summer (May through September, inclusive) or winter (the remaining months) |
| *Period* | on-peak (hours of the day 1100 through 1800, inclusive, during summer months only), mid-peak (0600 through 1000 and 1900 through 2200 during the summer, and 0600 through 2200 during the winter), or off-peak (0100 through 0500 and 2300 through 2400 during all months) |

*Customer Data*

| Name | Description |
|---|---|
| $Cload_{m,t,h}$ | customer load in kW during hour *h*, day type *t*, and month *m*. |

*Market Data*

| Name | Description |
|---|---|
| $RTPower_{s,p}$ | regulated demand charge under the default tariff for season *s* and period *p* ($/kW) |
| $RTEnergy_{m,t,h}$ | regulated tariff for energy purchases during hour *h*, type of day *t*, and month *m* ($/kWh) |
| $RTCCharge$ | regulated tariff customer charge ($) |
| $RTFCharge$ | regulated tariff facilities charge ($/kW) |
| $CTax$ | tax on carbon emissions ($/kg) |
| $MktCRate$ | carbon emissions rate from marketplace generation (kg/kWh) |
| $IEM_{m,t,h}$ | IEM price during hour *h*, type of day *t*, and month *m* ($/kWh) |

*Distributed Energy Resource Technologies Information*

| Name | Description |
|---|---|
| $DERmaxp_i$ | nameplate power rating of technology *i* ( kW) |
| $DERlifetime_i$ | expected lifetime of technology *i* (a) |
| $DERcapcost_i$ | overnight 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) |
| $CRate_i$ | carbon emissions rate from DER technology *i* (kg/kWh) |
| $DERCostkWh_i$ | production cost of technology *i* ($/kWh) |

*Other parameters*

| Name | Description |
|---|---|
| *IntRate* | interest rate on DER investments ( %) |
| *DiscoER* | disco non-commodity revenue neutrality adder[6] ($/kWh) |
| *FixRate* | fixed energy rate ($/kWh) applied in some cases[7] |
| $Solar_{m,h}$ | average fraction of maximum solar insolation received (%) during hour *h* and month *m* |
| *StandbyC* | standby charge in $/kW/month that SDG&E currently applies to its customers with autonomous generation |

#### 2.4.1.2 *Variables*

| ***Name*** | ***Description*** |
|---|---|
| $InvGen_i$ | number of units of the *i* technology installed by the customer |
| $GenL_{i,m,t,h}$ | generated power by technology *i* during hour *h*, type of day *t*, and month *m* to supply the customer's load ( kW) |
| $DRLoad_{m,t,h}$ [8] | residual customer load (purchased power from the distribution company by the customer) during hour *h*, type of day *t*, and month *m* (kW) |

### 2.4.2 Problem Formulation

There are two slightly different problems to be solved depending on how the μGrid acquires the residual electricity that it needs beyond its self-generation:

1. Buying that power from the distribution company (SDG&E) at the regulated tariff; or
2. Purchasing power at the IEM price plus an adder that would cover the non-commodity cost of delivering electricity.

In this work, a surcharge was introduced in the form of a revenue reconciliation term that was added to the IEM price or the fixed price. This term was calculated such that, if the μGrid's usage pattern were identical under the IEM pricing option and the regulated tariff option, the distribution company (disco) would collect identical revenue from the customer.

#### 2.4.2.1 *Option 1: Buying at the Default Regulated Tariff*

The mathematical formulation of the problem follows:

$$\min_{InvGen_i, GenL_{i,m,t,h}} \sum_m RTFCharge \cdot max(DRLoad_{m,t,h}) + \sum_m RTCCharge$$

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

[6] This value is added to the IEM price when the customer buys its power directly to the wholesale market. The *DiscoER* compensates the distribution company (disco) for transporting the electricity purchased from the IEM to the customer.

[7] If the model user selects this option the customer always buy its energy at the same price.

[8] 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.

$$+\sum_m\sum_t\sum_h DRLoad_{m,t,h}\cdot\left(RTEnergy_{m,t,h}+CTax\cdot MktCRate\right)$$

$$+\sum_i\sum_m\sum_t\sum_h GenL_{i,m,t,h}\cdot DERCostkWh_i$$

$$+\sum_i\sum_m\sum_t\sum_h GenL_{i,m,t,h}\cdot DEROMvar_i$$

$$+\sum_i\sum_m\sum_t\sum_h GenL_{i,m,t,h}\cdot CTax\cdot CRate_i$$

$$+\sum_i InvGen_i\cdot\left(DERcapcost_i+DEROMfix_i\right)\cdot AnnuityF$$

$$+\sum_m\sum_i InvGen_i\cdot DERmaxp_i\cdot StandbyC$$

(1)

Subject to:

$$Cload_{m,t,h}=\sum_i GenL_{i,m,t,h}+DRLoad_{m,t,h}\quad\forall_{m,t,h} \tag{2}$$

$$GenL_{i,m,t,h}\le InvGen_i\cdot DER\max p_i\quad\forall_{i,m,t,h} \tag{3}$$

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

$$GenL_{j,m,t,h}\le InvGen_j\cdot DER\max p_j\cdot Solar_{m,h}\quad\forall_{m,t,h}\ if\ j\in\{PV\} \tag{5}$$

$$\sum_m\sum_t\sum_h GenL_{i,m,t,h}\le InvGen_i\cdot DER\max p_i\cdot DERhours_i\ \forall_i \tag{6}$$

Equation (1) is the objective function which states that the μGrid will try to minimize total cost, consisting of total facilities and customer charges, total monthly demand charges, total energy charges (inclusive of carbon taxes), total on-site generation fuel and O&M costs, total on-site generation carbon taxes, total DER investment cost, and total standby charges, if applicable.

Equation (2) enforces energy balance. Equation (3) enforces the on-site generating capacity constraint. Equation (4) simply annualizes the capital cost of owning on-site generating equipment. If DER technology *j* is a photovoltaic (PV) cell, then equation (5) constrains it to generate in proportion to the solar insolation. Finally, equation (6) places an upper limit on how many hours each type of DER technology can generate during the year. 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 according to California legislation.

2.4.2.2 *Option 2: Buying from Alternative Energy Providers*

The problem's mathematical formulation follows:

$$\min_{InvGen_i, GenL_{i,m,t,h}} \quad \sum_m \sum_t \sum_h DRLoad_{m,t,h} \cdot \left(IEM_{m,t,h} + DiscoER + CTax \cdot MktCRate\right)$$

$$+ \sum_i \sum_m \sum_t \sum_h GenL_{i,m,t,h} \cdot DERCostkWh_i$$

$$+ \sum_i \sum_m \sum_t \sum_h GenL_{i,m,t,h} \cdot DEROMvar_i$$

$$+ \sum_i \sum_m \sum_t \sum_h GenL_{i,m,t,h} \cdot CTax \cdot CRate_i$$

$$+ \sum_i InvGen_i \cdot \left(DERcapcost_i + DEROMfix_i\right) \cdot AnnuityF$$

$$+ \sum_m \sum_i InvGen_i \cdot DERmaxp_i \cdot StandbyC$$

(1a)

Subject to:

Equations (2) through (6)

This formulation differs only in the objective function, equation (1a), which now charges the IEM price for each hourly time step plus the non-commodity revenue neutrality adder and the carbon tax. Note that the same mathematical formulation can be used if the model user wants to simulate a fixed price for all customer energy purchases. In that case, all IEM hourly prices are simply set to the fixed desired value.

## 3. Customer Description and Input Data

### 3.1 Load Shape Data

DER-CAM is run for a hypothetical μGrid composed of eight typical Southern California commercial electricity customers acting as one (a supermarket, an office, a sit-down restaurant, a fast food restaurant, a delicatessen, a department store, a retail store, and a warehouse store). An available archived set of commercial hourly load data that had been collected by Southern California Edison (SCE) in 1988-1989 (SCE 1989), (Akbari 1993) were used as the basis for the loads for the hypothetical customers.

The hourly annual data are organized into the day-types peak, weekday, and weekend as described in Section 2.4.1.1. A sample load profile is presented in Figure 1.

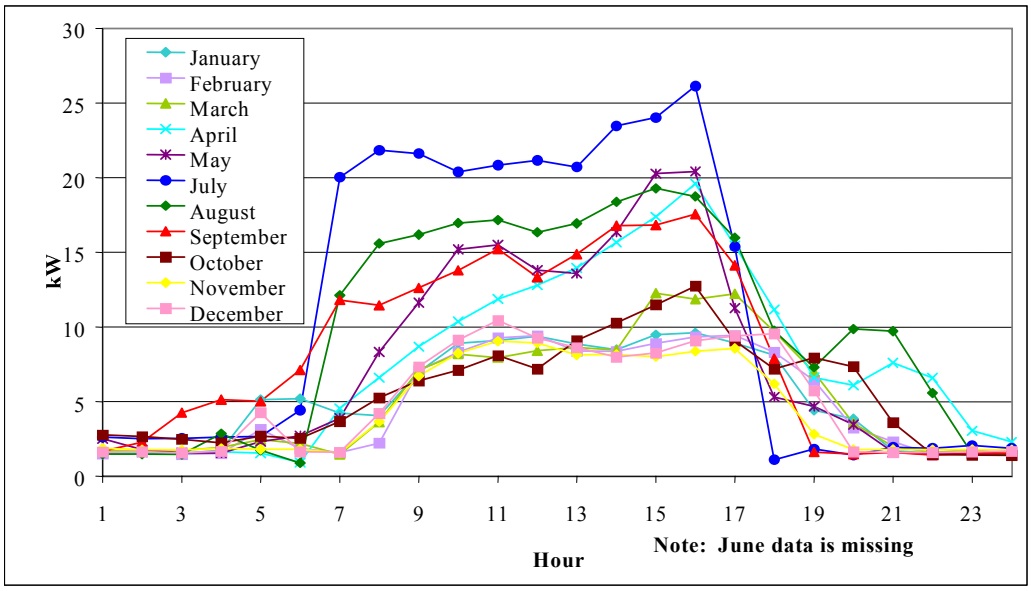


**Figure 1. Office Monthly Peak Load**

Table 1. Illustrates the composition of the µGrid as chosen for this a nalysis.

**Table 1. µGrid Summary**

| Type of Business | Name of Site | Floor Area ($m^2$) | Tot. Ann. Energy (kWh) | Energy Density ($kWh/m^2 \cdot a$) | Peak Load (kW) | Peak Hour | Load Factor | Data Comments |
|---|---|---|---|---|---|---|---|---|
| 1. Supermarket | Dangerway | 1,536 | 1,708,581 | 1,112 | 255 | Sept 15:00 | 76% | complete |
| 2. Office | Great Vistas Real Estate | 223 | 40,269 | 181 | 26 | July 16:00 | 18% | june missing |
| 3. Sitdown Restaurant | Nan Hideaway | 1,003 | 529,231 | 528 | 110 | Sept 17:00 | 55% | complete |
| 4. Fast Food Restaurant | Burger Queen | 339 | 487,973 | 1,439 | 100 | July 12:00 | 55% | complete |
| 5. Deli Restaurant | Sub Safe Harbor | 674 | 199,553 | 296 | 56 | July 13:00 | 41% | complete |
| 6. Department Store | Spacy's | 6,466 | 1,459,949 | 226 | 309 | Sept 12:00 & 15:00 | 54% | complete |
| 7. Retail Store | Drum Buster Stereo | 1,347 | 263,367 | 196 | 81 | July 13:00-16:00 | 37% | complete |
| 8. Warehouse Store | Ram's Club | N/A | 1,821,001 | N/A | 299 | July 15:00 | 69% | complete |
| 9. Total Microgrid | Microgrid Oaks Mall | 11,588* | 6,370,206 | 405* | 1253 | July 14:00 | 58% | june missing |

* not including warehouse since floor area data is not available

## 3.2 SDG&E Tariff and IEM Prices

µGrid s purchasing electricity from their disco are assumed to do so under established 2000 tariffs. In this study, three publicly available tariff rates for commercial customer types are used (see Table 2), depending on the size of the customer's peak load. For each tariff type, a monthly-ratcheted demand charge and an energy charge are imposed and vary seasonally.

The load periods (on-peak, mid-peak, and off-peak) are defined differently under each season. In addition, a fixed charge per customer per month is levied (see Table 3).[9]

**Table 2. SDG&E AL-TOU (General Service Time-of-Use) Tariff Information**

| Season | Load Period | Demand Charge (US$/kW) | Energy Charge (US$/kWh) |
|---|---|---|---|
| summer | on-peak | 9.00 | 0.21262 |
| summer | mid-peak | 5.78 | 0.11851 |
| summer | off-peak | 5.78 | 0.07442 |
| winter | on-peak | 0.00 | 0.00000 |
| winter | mid-peak | 5.78 | 0.11281 |
| winter | off-peak | 5.78 | 0.06995 |

**Table 3. SDG&E AL-TOU Fixed Customer Charges**

| Customer Charge (US$/month) | Stand-by Charge (US$/kW/month) |
|---|---|
| 43.50 | 0.00 |

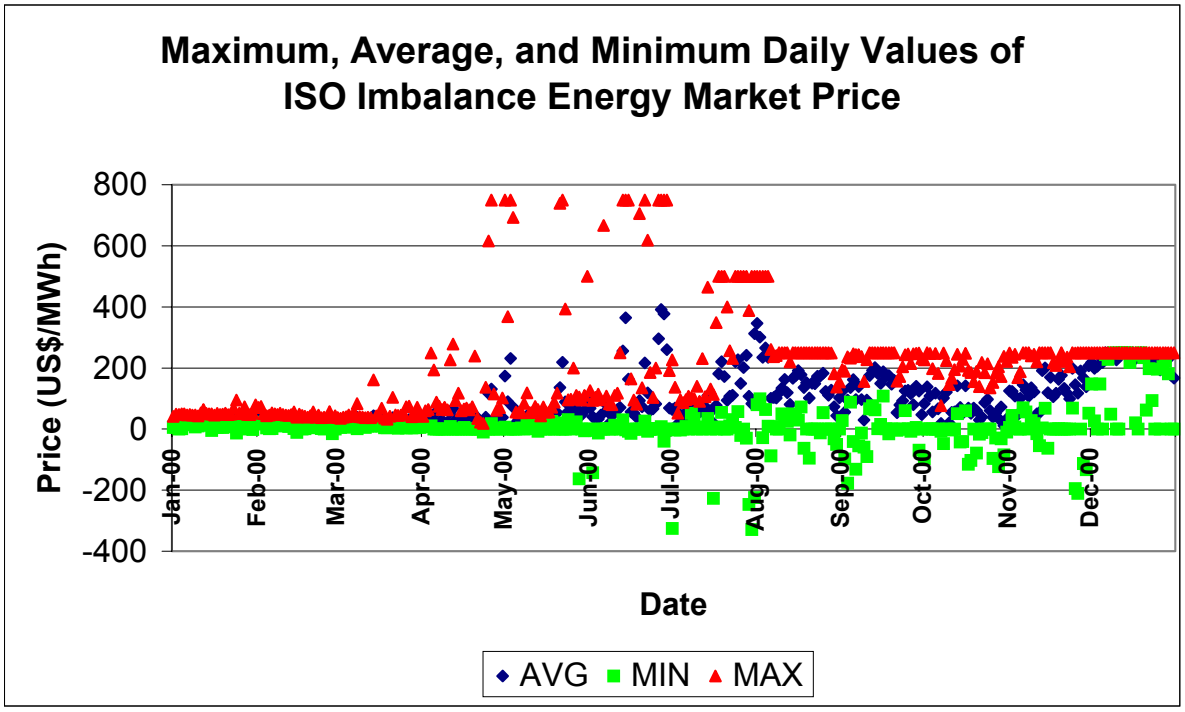


**Figure 2. California Independent System Operator (CAISO) IEM Price Summary for 2000**

For California, the competitive electricity price generally refers to the CAISO IEM price, essentially a spot market for electricity. Figure 2. summarizes market prices for 2000. In general, the IEM prices were within their historical ranges (i.e., less than US$50/MWh) for the first half of the year. By July 2000, however, the combination of supply constraints,

[9] In the U.S. peak power charges are usually called *demand charges*.

burgeoning natural gas prices (which is burned by most generators to produce electricity), and inelastic consumer demand drove the IEM price to the artificially imposed price caps.[10]

### 3.3 Generating Technology Data

The generating technologies available to the customers are listed in Table 4. along with their operating characteristics. The technologies beginning with labels *MT* are microturbines, manufactured by Capstone. *PAFC* is a phosphoric acid fuel cell (*FC*) made by ONSI (now known as UTC Fuel Cells).

Those beginning with *DE-K* and *DE-C* are diesel backup generators manufactured by Katolight and Cummins/Onan, respectively. The rest of the technologies are various brands of Katolight natural gas backup generators (labeled by *GA-K*) and photovoltaic systems (*PV*). The solar insolation data, which indicate the fraction of maximum historical solar insolation received in the Southern California test area, are provided by the National Renewable Energy Laboratory (NREL, http://www.nrel.gov).[11] Figure 3. illustrates how available sunlight changes throughout the year and affects PV operation decisions. This is accounted for by equation (5) in Sections 2.4.2.1 and 2.4.2.2.

**Table 4. DER Technology Characteristics**

| Technology | Name-plate (kW) | Lifetime (a) | Turnkey Cost (US$/kW) | OMFix (US$/kW/a) | OMVar (US$/kWh) | Heat Rate (kJ/kWh) | Source | Fuel |
|---|---|---|---|---|---|---|---|---|
| MTL-C-30 | 30 | 12.5 | 1333 | 119 | 0 | 12,186 | SCE | natural gas |
| MTH-C-30 | 30 | 12.5 | 1333 | 119 | 0 | 12,186 | SCE | natural gas |
| PAFC-O-200 | 200 | Proprietary | Proprietary | Proprietary | Proprietary | Proprietary | Proprietary | natural gas |
| DE-K-15 | 15 | 12.5 | 2257 | 26.5 | 0.000033 | 18,288 | Manu | diesel |
| DE-K-30 | 30 | 12.5 | 1290 | 26.5 | 0.000033 | 11,887 | Manu | diesel |
| DE-K-60 | 60 | 12.5 | 864 | 26.5 | 0.000033 | 11,201 | Manu | diesel |
| DE-K-105 | 105 | 12.5 | 690 | 26.5 | 0.000033 | 10,581 | Manu | diesel |
| DE-K-200 | 200 | 12.5 | 514 | 26.5 | 0.000033 | 11,041 | Manu | diesel |
| DE-K-350 | 350 | 12.5 | 414 | 26.5 | 0.000033 | 10,032 | Manu | diesel |
| DE-K-500 | 500 | 12.5 | 386 | 26.5 | 0.000033 | 10,314 | Manu | diesel |
| DE-C-7 | 7.5 | 12.5 | 627 | 26.5 | 0.000033 | 10,458 | Manu | diesel |
| DE-C-20 | 20 | 12.5 | 1188 | 26.5 | 0.000033 | 12,783 | Manu | diesel |
| DE-C-40 | 40 | 12.5 | 993 | 26.5 | 0.000033 | 11,658 | Manu | diesel |
| DE-C-100 | 100 | 12.5 | 599 | 26.5 | 0.000033 | 10,287 | Manu | diesel |
| DE-C-200 | 200 | 12.5 | 416 | 26.5 | 0.000033 | 9,944 | Manu | diesel |
| DE-C-300 | 300 | 12.5 | 357 | 26.5 | 0.000033 | 10,287 | Manu | diesel |
| DE-C-500 | 500 | 12.5 | 318 | 26.5 | 0.000033 | 9,327 | Manu | diesel |
| GA-K-25 | 25 | 12.5 | 1730 | 26.5 | 0.000033 | 15,596 | Manu | natural gas |
| GA-K-55 | 55 | 12.5 | 970 | 26.5 | 0.000033 | 12,997 | Manu | natural gas |
| GA-K-100 | 100 | 12.5 | 833 | 26.5 | 0.000033 | 15,200 | Manu | natural gas |
| GA-K-215 | 215 | 12.5 | 1185 | 26.5 | 0.000033 | 13,157 | Manu | natural gas |
| GA-K-500 | 500 | 12.5 | 936 | 26.5 | 0.000033 | 12,003 | Manu | natural gas |
| PV-5 | 5 | 20 | 8650 | 14.3 | 0 | 0 | Jeff Oldman, Real Goods | sun |
| PV-20 | 20 | 20 | 7450 | 14.3 | 0 | 0 | Jeff Oldman, Real Goods | sun |
| PV-50 | 50 | 20 | 6675 | 12 | 0 | 0 | Jeff Oldman, Real Goods | sun |
| PV-100 | 100 | 20 | 6675 | 11 | 0 | 0 | Jeff Oldman, Real Goods | sun |

[10] These were first US$750/MWh, but were later lowered to US$250/MWh.

[11] The "peak" insolation refers to the historically accepted peak value of 1050 Wh/m$^2$, which is less than the peak value in the data set (1303 Wh/m$^2$). These data are for San Diego, CA (latitude N 32 44, longitude W 117 10, and elevation 9 m) from 1990. Furthermore, the peak rating is under certain test conditions, and field performance can exceed the test condition.

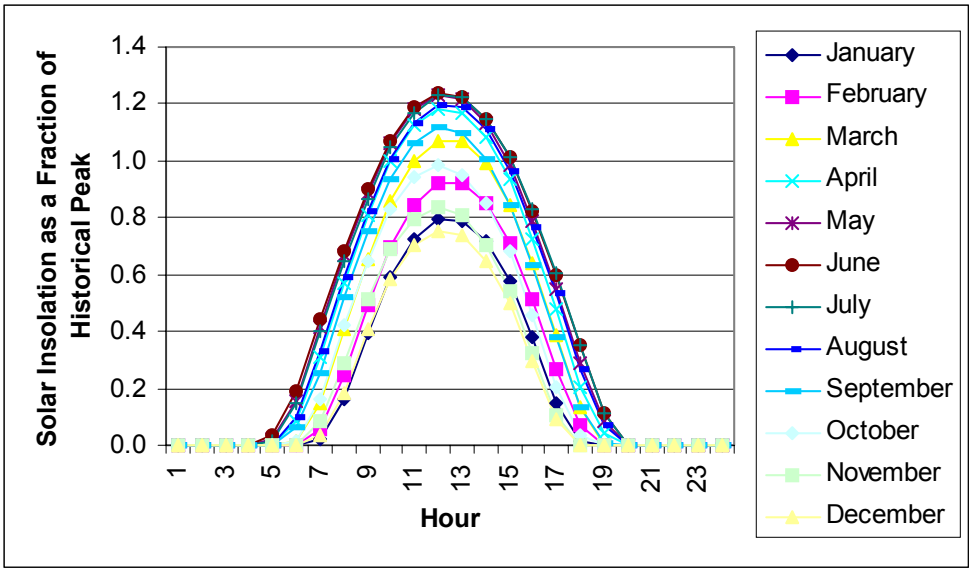


**Figure 3. Solar Insolation as a Fraction of Historical Peak Value Received in the Southern California Test Area**

3.4 Fuel Data

The fuel prices and carbon emissions data are summarized by Table 5. In order to obtain the actual carbon emissions (in kg/kWh) for any particular technology, simply multiply the heat rate of the technology (from Table 4) by the appropriate carbon emissions rate of the corresponding fuel. For electricity that is generated offsite, i.e., electricity purchased from the IEM or SDG&E, the average annual carbon emissions rate is 0.13 kg/kWh. Note that while both the natural gas and diesel prices varied considerably throughout 2000, it is assumed that the μGrid hedges against such price volatility by signing long-term contracts. Hence, it pays a constant price for fuel throughout the year, which is equal to the mean price. In future work, we anticipate incorporating the seasonal variation in fuel prices; but here we abstract from this feature to focus on electricity prices and generation.

**Table 5. Fuel Data**

| Fuel | Price (US$/kJ) | Carbon Emissions Rate (kg/kJ) |
|---|---|---|
| Sun | 0.00 | 0.00 |
| Natural Gas | $8.25 \times 10^{-6}$ | $1.3715 \times 10^{-5}$ |
| Diesel | $8.46 \times 10^{-6}$ | $1.8909 \times 10^{-5}$ |

3.5 Carbon Costs

It is likely that a carbon emissions market will emerge in the next few years, starting in industrialized countries that have shown active interest in fulfilling the Kyoto climate change protocol. The market mechanisms will ensure that the most cost-effective options are selected to mitigate carbon emissions.

Although there is still considerable uncertainty in the magnitude of carbon costs, recent studies in the USA and in the European Union indicate a large savings potential, both in the

supply- and demand-side, with a tax of less than US$100 per metric ton (t) of carbon. In the European Climate Change Program, it was shown that the European Union could reduce its carbon emissions in 2010 by 8%, using technology options under a tax of US$70/t (see E.C. 2001).

## 4. Results

In this chapter, we examine the implications that a carbon tax has on DER investment and carbon emissions. In order to insure that our analysis is robust, it is performed under various regulatory and economic conditions, summarized by Table 6. We find that a carbon tax generally stimulates DER investment, especially if additional subsidies are given for the installation of "green" (or, environmentally friendly) technologies, such as PVs and FCs. In turn, this greater DER investment in "green" technologies enables a reduction in operating costs for the μGrid relative to purchasing electricity from the macrogrid.

Similarly, if "green" subsidies are present, a carbon tax of US$500/t is enough to reduce carbon emissions by over a third relative to the case with no carbon tax. Absent such subsidies, comparable reductions in emissions are possible only for higher levels of carbon tax. In order to provide a basis for comparison, we determine both the minimum and maximum levels of carbon emissions that could be produced. While the carbon emitted by the μGrid in our model is not driven to the minimum level possible; we find that a carbon tax of US$500/t along with "green" subsidies is enough to reduce emissions to less than 75% of the maximum level.

**Table 6. Operating Scenarios for Purchasing Electricity**

| Operating Scenarios and Sensitivities | Description |
|---|---|
| Base (IEM) | In this scenario, the μGrid can buy all of its electricity requirements at the IEM price. However, it also has to pay an extra fee in order to achieve revenue neutrality for the disco (compared with the tariff scenario, described next). This solves the model in Section 2.4.2.2. |
| Disco (SDG&E) | In this scenario, the μGrid buys all of its electricity from the disco at an established tariff structure. This solves the model in Section 2.4.2.1. |
| 25% Subsidy | Same as "base," but all “green” technologies (such as fuel cells and photovoltaics) are given a 25% state subsidy towards their turnkey costs. |
| 50% Subsidy | Same as "25 % subsidy," but now the subsidy is increased to cover 50% of the turnkey costs. |

### 4.1 Effect of Carbon Tax on Generation

Intuitively, the effect of a carbon tax would be to stimulate the adoption of "greener" generation technologies since they emit less carbon per kWh of electricity produced. Within the context of our μGrid model with DER options, such a tax encourages the μGrid to increase investment in "green" DER technologies, such as PVs. This transition, however, usually does not occur until the carbon tax is hundreds of dollars per metric ton (see Figure 4 to Figure 8). Indeed, for all cases except when “green” technologies receive a 50% turnkey cost subsidy, the presence of a carbon tax is not enough incentive for the μGrid to adopt "green" technologies unless the carbon tax is greater than US$400/t. For values of the carbon

tax lower than this value, the μGrid finds it cheaper to meet its electricity needs through the macrogrid (either the IEM or the disco SDG&E) and DER technologies that use natural gas. It is only in the 50% “green” technologies subsidy case that the μGrid finds it attractive to install "green" DER technologies such as PVs for low values of the carbon tax. In fact, it installs a small PV system even without a carbon tax.

In order to assess the effect of the carbon tax on actual onsite energy generation, the fraction of electricity that the μGrid produces with DER in the four cases is shown by Figure 9. to Figure 12. Again, the general trend is that the fraction of energy produced onsite decreases slightly until the carbon tax is high enough to make installation of PVs economically attractive and spurs more onsite generation. This transition towards PV adoption occurs for lower levels of carbon tax in the 50% "green" technologies subsidy case. Nevertheless, the fraction of energy generated onsite in all cases starts off at about 50% and increases to 60% with the carbon tax. The only case that deviates from such behavior is the disco case, in which the evening tariff rate is low enough to deter usage of DER technologies during off-peak hours. Hence, because the PVs cannot operate during these hours, the μGrid does not reduce its dependence on the macrogrid in the disco case.

A corollary effect of the carbon tax is that it enables the μGrid to reduce its costs through DER investment. In the same figures, we plot on a secondary axis the percentage cost savings that accrue to the μGrid due to its having the option to invest in DER technologies. In other words, we compare the costs of using *only* the macrogrid with the costs of supplementing macrogrid purchases with DER investment. For all cases, the cost savings from having the option to install DER decrease until the carbon tax reaches a critical value. This is because for low levels of carbon taxation, the μGrid increases its macrogrid purchases. It is not until the carbon tax is high enough that PV installation is cost-effective, and thereby, reduces the μGrid 's reliance on the macrogrid. This effect is illustrated by Table 7, in which the fraction of carbon emissions from the macrogrid increases with the carbon tax even as the fraction of energy generated by it decreases. While the carbon tax makes the μGrid better off in a *relative* sense (i.e., compared to the case in which it is solely reliant on the macrogrid), it, nevertheless, results in *absolute* cost increases. Figure 13. indicates that for all cases, a carbon tax on the order of US$1000/t is enough to double the μGrid 's costs.

The effect of the carbon tax is to encourage investment in "green" DER technologies. In general, such adoption also results in the μGrid's satisfying a larger fraction of its energy needs through onsite generation than in the case without a carbon tax. Furthermore, the option to install DER technologies enables the μGrid to reduce costs by about 20% from the situation in which no DER technologies are available. These benefits, however, don't begin to accrue until the carbon tax exceeds US$400/ton. Only when substantial (e.g., 50%) turnkey cost subsidies are given to "green" technologies is it immediately attractive for the μGrid to install DER technologies in response to carbon taxation.

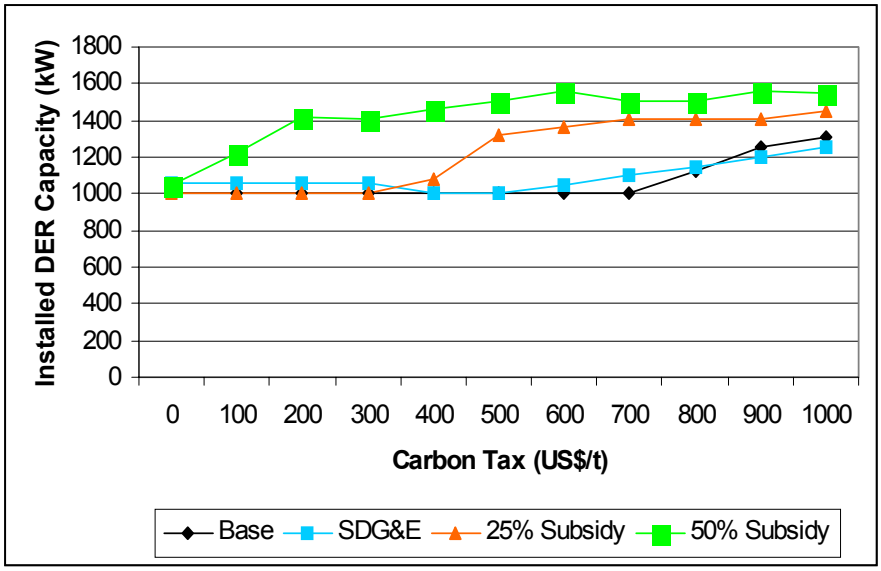


**Figure 4. Installed DER Capacity**

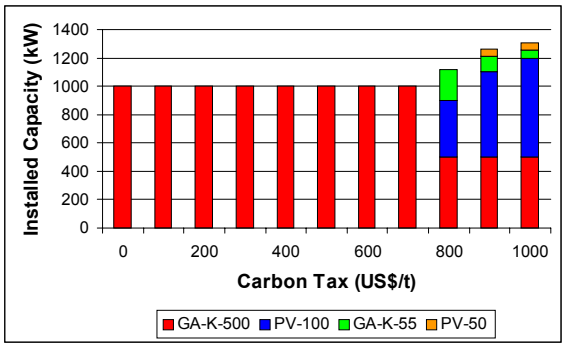


**Figure 5. Installed DER Technologies for the Base Case**

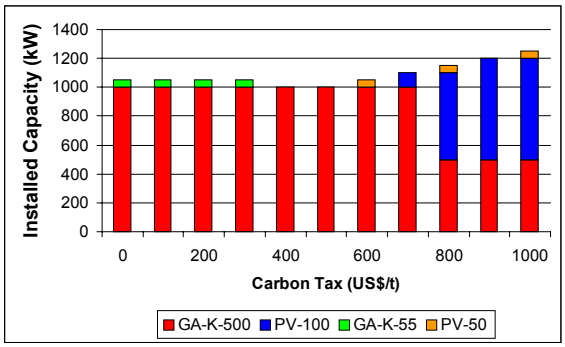


**Figure 6. Installed DER Technologies for the Disco SDG&E Tariff Case**

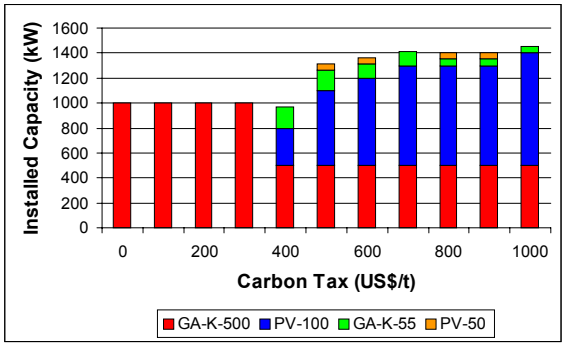


**Figure 7. Installed DER Technologies for the 25% Subsidy Case**

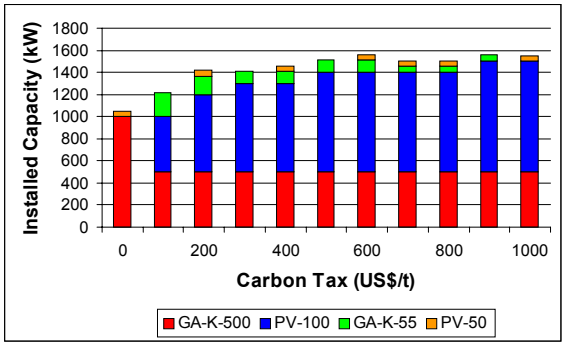


**Figure 8. Installed DER Technologies for the 50% Subsidy Case**

## Table 7. Percentage of Carbon Emissions from Macrogrid

| Carbon Tax (US$/t) | Base Case | SDG&E Case | 25% Subsidy | 50% Subsidy |
|---|---|---|---|---|
| 0 | 44% | 42% | 44% | 45% |
| 100 | 45% | 44% | 45% | 59% |
| 200 | 46% | 45% | 46% | 71% |
| 300 | 47% | 46% | 47% | 76% |
| 400 | 48% | 46% | 55% | 79% |
| 500 | 48% | 47% | 70% | 82% |
| 600 | 48% | 48% | 75% | 84% |
| 700 | 49% | 50% | 79% | 87% |
| 800 | 52% | 65% | 71% | 75% |
| 900 | 57% | 61% | 65% | 70% |
| 1000 | 60% | 62% | 66% | 71% |

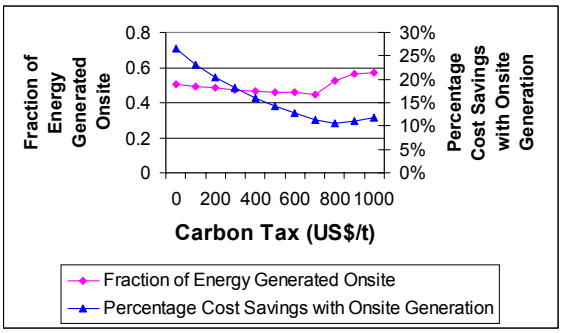


**Figure 9. Effect of Carbon Tax on Energy Generation and Costs for the Base Case**

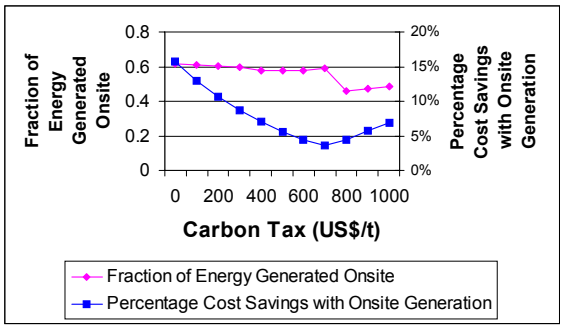


**Figure 10. Effect of Carbon Tax on Energy Generation and Costs for the Disco SDG&E Tariff Case**

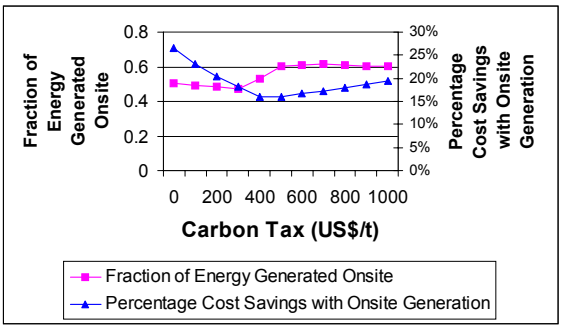


**Figure 11. Effect of Carbon Tax on Energy Generation and Costs for the 25% Subsidy Case**

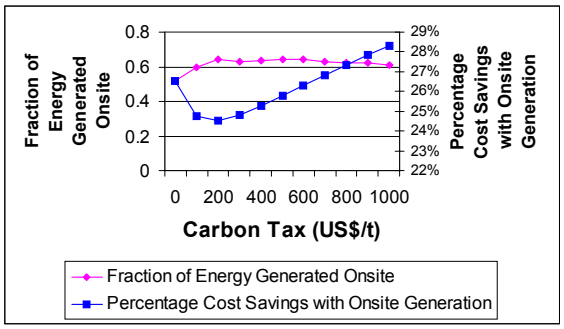


**Figure 12. Effect of Carbon Tax on Energy Generation and Costs for the 50% Subsidy Case**

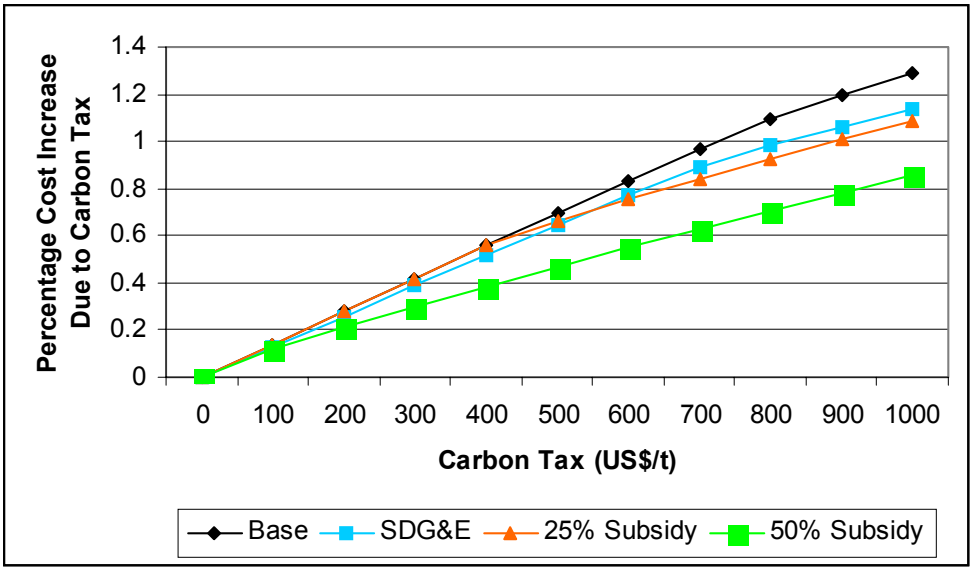


**Figure 13. Percentage Cost Increase Due to Carbon Tax**

## 4.2 Effect of Carbon Tax on Emissions

The effect of the carbon tax on carbon emissions is similar to its effect on DER adoption and µGrid costs. In general, the environmental impact of a carbon tax of US$700/t is to reduce cumulative carbon emissions by over 40% from a scenario with no carbon tax (see Figure 14). Although carbon taxes provide an impetus for the µGrid to invest in ("green") DER technologies to reduce carbon emissions for carbon tax levels less than US$500/t, they have only marginal impact. Indeed, with a macrogrid carbon emissions rate of 0.13 kg C/kWh[12], it is not economically viable for the µGrid to invest in DER technologies in response to carbon taxation, unless the carbon tax exceeds US$400/t. Only for the 50% "green" technologies subsidy case is investment in "green" DER technologies effective at low levels of carbon taxation.

In the disco tariff case, carbon emissions decrease by a greater amount than they do in the IEM case, even though a greater proportion of the µGrid 's energy needs are met through onsite generation in the latter case. This is because the higher peak (i.e., daytime) tariff rates together with the high carbon emissions rates of conventional DER technologies encourage a migration to "green" DER technology adoption at lower levels of carbon taxation than in the IEM case. For the same level of carbon tax, the IEM peak prices are lower than the disco tariff rates, thereby delaying the adoption of "green" DER technologies and the abatement of carbon emissions.

While the carbon tax does eventually result in almost halving the level of carbon emissions, how does it compare to other carbon control policies? Here, we consider two other policies:

1. A *macrogrid only* (MO) policy in which the µGrid is taxed for carbon emissions, but is not permitted to install DER technologies. In this policy, the µGrid solves the model in Section 2.4.2.1 (or Section 2.4.2.2 if it purchases electricity from the IEM), but with $InvGen_i = 0 \; \forall \; i$ (and therefore, with $GenL_{i,m,t,h} = 0 \; \forall \; i,m,t,h$).

[12] This compares favorably with rates of 0.16 kg C/kWh and 0.18 kg C/kWh for the most efficient natural gas and diesel DER technologies, respectively.

2. A *perfectly green* (PG) policy in which the µGrid is mandated to minimize its carbon emissions only instead of its combined costs. Here, the objective function is simply $\min_{InvGen_i, GenL_{i,m,t,h}} \sum_i \sum_m \sum_t \sum_h \left( DRLoad_{m,t,h} \cdot MktCRate + GenL_{i,m,t,h} \cdot CRate_i \right)$ instead of equation (1) or (1a). This is essentially a situation in which PVs supply electricity during the day, and the macrogrid provides electricity at night. As usual, DER technology investment is permitted.

In Figure 15 to Figure 18, we plot the carbon emissions from using the *combined cost function* (CCF), i.e., the one described by equations (1) and (1a), along with the carbon emissions under the MO and PG policies. Note that because the MO and PG policies are static, the level of carbon emissions does not vary with the carbon tax. For low levels of carbon taxation, we find that the level of carbon emissions under the CCF exceeds the carbon emissions from both the MO and PG policies. Once the carbon tax increases to about US$500/t, carbon emissions under the CCF decline to below the MO policy levels as "green" DER technology investment becomes attractive. For the 50% "green" technology subsidy case, this transition occurs for a lower level of taxation. After "green" DER technology is installed and used regularly, carbon emissions continue to decline. For very high levels of carbon tax, i.e., around US$1000/t, carbon emissions begin to approach the levels yielded by the PG policy. This decline is gradual, and even in the 50% “green” technology subsidy case with a US$1000/t carbon tax, carbon emissions remain one and a half times as high as they are with the PG policy.

The near halving of carbon emissions from pre-tax levels is the ultimate result of the carbon tax. This reduction, however, occurs only for relatively high levels of carbon tax as the high turnkey cost of most "green" DER technologies proves too big a barrier to their adoption. An effective methodology for reducing carbon emissions, therefore, is to provide a subsidy towards the turnkey costs of "green" technologies. Within the context of this model, the latter approach achieves the greatest reduction in carbon emissions at the lowest levels of carbon taxation.

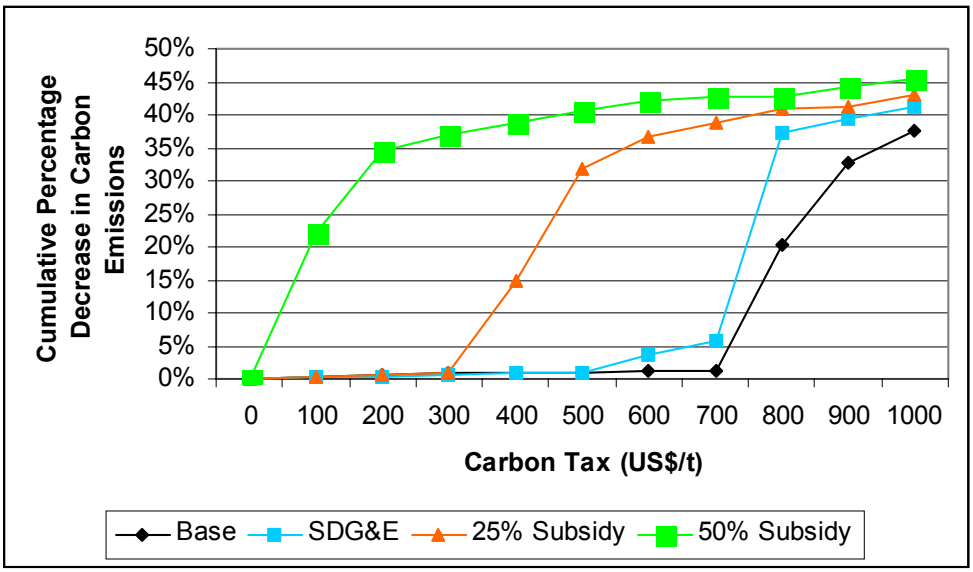


**Figure 14. Cumulative Percentage Decrease in Carbon Emissions**

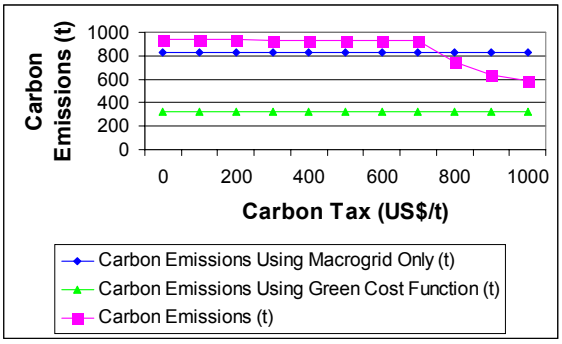


**Figure 15. Carbon Emissions Comparison for the Base Case**

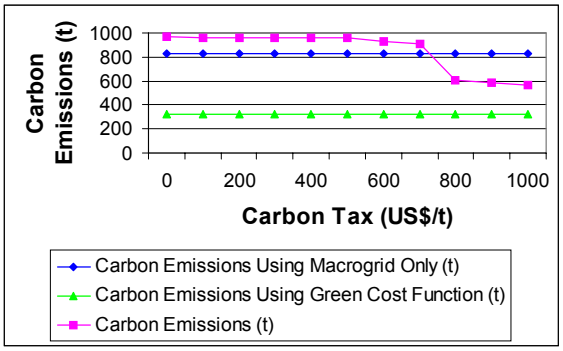


**Figure 16. Carbon Emissions Comparison for the Disco SDG&E Tariff Case**

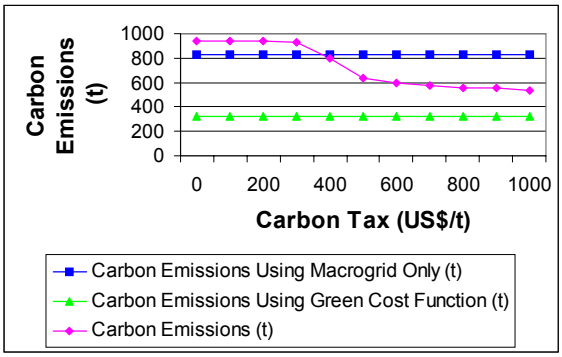


**Figure 17. Carbon Emissions Comparison for the 25% Subsidy Case**

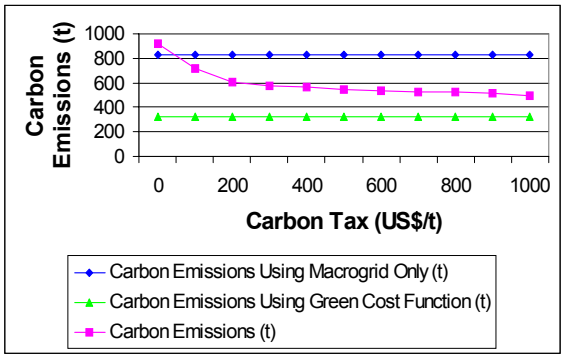


**Figure 18. Carbon Emissions Comparison for the 50% Subsidy Case**

## 5. Conclusions

In this paper, we construct an economic model to evaluate the effect of DER technology adoption by a hypothetical µGrid on carbon emissions. The µGrid contains California commercial customers. It has to meet its electricity load at minimum cost either by purchasing electricity from the macrogrid or by installing onsite generation resources. Its costs include carbon taxes in addition to the costs of purchasing electricity, installing DER technologies, and operating and maintaining DER technologies. By solving the resulting optimization problem in GAMS, we obtain the extent of DER technology adoption and resulting carbon emissions for a given regulatory environment and level of carbon taxation.

We find that while DER technology adoption increases with carbon taxation, the effect is not uniform, since non-renewable DER technology generates electricity with a higher carbon content than the electricity provided by the macrogrid. In most cases, the carbon tax must exceed US$400/t before "green" DER technologies are adopted. Similarly, the impact of the carbon tax on carbon emissions abatement is marginal for carbon tax levels below US$400/t. Indeed, some carbon emissions abatement does occur for low levels of carbon taxation, but this is a consequence of the µGrid's purchasing more electricity from the macrogrid, which has a slightly lower carbon emissions rate than most of the DER technologies. Only when the turnkey costs of "green" technologies are reduced by 50%, that significant (i.e., greater than 20%) carbon emissions abatement is realized at carbon tax levels less than US$400/t. Hence, according to our model, the most effective strategy for reducing carbon emissions is to provide a significant subsidy towards the turnkey costs of "green" technologies. The

subsidies are also likely to accelerate a significant decline the costs of these technologies during the coming years. This will enable a greater reduction in carbon emissions at a lower level of carbon taxation.

In future work, the model will be enhanced by including hourly variations in the macrogrid carbon emissions rate, seasonal variation in the fuel prices, more "green" DER technologies, and CHP. In particular, with CHP, the μGrid 's cost of satisfying both electricity and heat loads could be jointly optimized. CHP will give the μGrid more opportunity to reduce its carbon emissions as well as improve the economics, thereby inducing more DER technology adoption.

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