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# Distributed Energy Resources for Carbon Emissions Mitigation

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# Disclaimer

# Distributed Energy Resources for Carbon Emissions Mitigation

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## Keywords

carbon tax, combined heat and power, distributed energy resources, greenhouse gas, optimization, United States legislation

## Abstract

The era of publicly mandated GHG emissions restrictions in the United States has begun with recent legislation in California and seven northeastern states. Commercial and industrial buildings can improve the carbon-efficiency of end-use energy consumption by installing technologies such as on-site cogeneration of electricity and useful heat in combined heat and power systems, thermally-activated cooling, solar electric and thermal equipment, and energy storage - collectively termed distributed energy resources (DER). This research examines a collection of buildings in California, the Northeast, and the southern United States to demonstrate the effects of regional characteristics such as the carbon intensity of central electricity grid, the climate-driven demand for space heating and cooling, and the availability of solar insolation. The results illustrate that the magnitude of a realistic carbon tax ($100/tC) is too small to incent significant carbon-reducing effects on economically optimal DER adoption. In large part, this is because cost reduction and carbon reduction objectives are roughly aligned, even in the absence of a carbon tax.

## Introduction

Distributed energy resources (DER) such as on-site fossil-fuel based combined heat and power (CHP), thermally-activated cooling, photovoltaics, solar thermal collectors, and energy storage devices can be used to reduce energy costs and/or site-attributable carbon emissions at commercial and industrial scale sites. The recent introduction of greenhouse gas (GHG) emissions regulations in several U.S. states suggest the possibility that an economic mechanism such as a carbon tax might be imposed. This poster illustrates how economically optimal distributed energy resource (DER) investment and resulting carbon emissions would be affected by a hypothetical carbon tax imposed on both electricity and natural gas purchase. Three commercial building types in three U.S. cities are modelled; an economic optimization of DER investment and operation is performed on each.

## Distributed Energy Resources Customer Adoption Model

This research uses the Distributed Energy Resources Customer Adoption Model (DER-CAM) to identify economically optimal DER. DER-CAM employs investment and operations optimization algorithms developed at the Berkeley Lab with a composite of capabilities described in Firestone, Marnay, and Wang (2005), Siddiqui et al. (2007), and Marnay et al. (2007). Optimization techniques find both the combination of DER equipment and its operation over a typical year that minimizes the site's total energy bill, typically for electricity, natural gas, and amortized DER capital costs. DER-CAM solves the commercial building DER investment optimization problem given a building's end-use energy loads, energy tariff structures and fuel prices, and DER equipment investment options. The approach is fully technology neutral and can include energy purchases, on-site conversion, both electrical and thermal on-site renewable harvesting, and electrical and thermal storage. The electrical and thermal problems are coupled by the use of thermally activated cooling to displace electric cooling loads, and by the simultaneous cogeneration of electricity and heat from CHP. The economics of storage is particularly complex, both because it requires optimization across multiple time steps and because of the influence of tariff structures. Regulatory, engineering, and investment constraints are all considered. Energy costs are calculated using a detailed representation of utility tariff structures and fuel prices, as well as amortized DER investment costs, and operating and maintenance (O&M) expenditures.

The result of DER-CAM is a cost minimizing DER equipment combination and operation schedule for the site; however, the rigors of optimization necessitate simplification of many real-world engineering constraints that would in practice necessarily be addressed through more detailed engineering analysis and system design.

## Site Selection and Data Collection

Buildings considered here are a subset of buildings considered in LaCommare et al. (2006), which reports the details of building modelling, size selection and data collection. For this poster, three prototypical commercial buildings, healthcare, lodging, and office, were used. Healthcare and lodging are typically favorable DER host candidates because of their consistent loads and balanced heat and electricity requirements, i.e. there are adequate uses for generator waste heat, rare in warm climates. Offices are typically unfavorable DER candidates because there are many times (nights, weekends) when DER investments cannot be utilized. Each building type is modelled in both a small (peak electric load ~300-500 kW) and a large size (peak electric load ~1-2 MW). Even smaller sites are assumed too small for DER investment and even larger sites are assumed to adopt different technologies than those modelled in DER-CAM.

Each of these six buildings is modelled in three cities: Atlanta, Georgia, Boston, Massachusetts, and San Francisco, California. California and Massachusetts are states with relatively high energy prices and with GHG mitigation legislation. Atlanta, in contrast, has neither of these. Together, these 18 sites (3 building types x 2 sizes x 3 cities) represent a range of DER attractiveness in the U.S.

DER investment cost and performance data is derived from Goldstein et al. (2003), Gaiam Real Goods (2007), and various manufacturers' specifications. DER technologies in DER-CAM are categorized as either discretely sized technologies or continuously sized technologies. Discretely sized technologies are only available in a limited number of sizes, such as electric generators; there is a fixed capital cost for each unit. Continuously sized technologies are available in numerous sizes; for these technologies there is a fixed cost ($) for investment of any size, and a variable cost ($/kW or $/kWh) proportional to the capacity of the equipment installed.

Table 1 shows energy consumption, cost, and carbon emissions data for the 18 sites, Table 2 shows the 2004 energy costs for commercial customers in the three cities, and

Table 3 shows DER technology cost and performance data. Marginal carbon emissions rate from central grid electricity production were obtained from The Climate Trust (2005) and were 0.179, 0.149, and 0.134 kgC/kWh for Atlanta, Boston, and San Francisco respectively.

**Table 1. no-invest energy details**

| | | | *electicity* | | | | *natural gas* | | | *total* | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **building type** | **size** | **city** | **peak electric load (MW)** | **consumption (GWh/a)** | **cost (M$/a)** | **carbon emissions (kt/a)** | **consumption (GWh/a)** | **cost (M$/a)** | **carbon emissions (kt/a)** | **total energy cost (M$/a)** | **total carbon emissions (kt/a** |
| ***health care*** | ***small*** | ***Altanta*** | 0.58 | 3.45 | 0.21 | 0.62 | 1.49 | 0.06 | 0.07 | 0.27 | 0.69 |
| ***health care*** | ***large*** | ***Altanta*** | 1.19 | 7.09 | 0.43 | 1.27 | 2.45 | 0.09 | 0.12 | 0.52 | 1.39 |
| ***lodging*** | ***small*** | ***Altanta*** | 0.46 | 2.10 | 0.13 | 0.38 | 0.56 | 0.02 | 0.03 | 0.15 | 0.40 |
| ***lodging*** | ***large*** | ***Altanta*** | 1.97 | 9.04 | 0.55 | 1.62 | 2.42 | 0.09 | 0.12 | 0.64 | 1.74 |
| ***office*** | ***small*** | ***Altanta*** | 0.35 | 1.22 | 0.08 | 0.22 | 0.37 | 0.01 | 0.02 | 0.09 | 0.24 |
| ***office*** | ***large*** | ***Altanta*** | 1.40 | 4.99 | 0.31 | 0.89 | 0.84 | 0.03 | 0.04 | 0.34 | 0.93 |
| ***health care*** | ***small*** | ***Boston*** | 0.56 | 3.23 | 0.36 | 0.48 | 2.16 | 0.09 | 0.11 | 0.45 | 0.59 |
| ***health care*** | ***large*** | ***Boston*** | 1.15 | 6.61 | 0.74 | 0.98 | 3.74 | 0.15 | 0.18 | 0.89 | 1.17 |
| ***lodging*** | ***small*** | ***Boston*** | 0.42 | 1.86 | 0.22 | 0.28 | 0.86 | 0.04 | 0.04 | 0.26 | 0.32 |
| ***lodging*** | ***large*** | ***Boston*** | 1.80 | 8.06 | 0.96 | 1.20 | 3.72 | 0.15 | 0.18 | 1.11 | 1.38 |
| ***office*** | ***small*** | ***Boston*** | 0.35 | 1.14 | 0.16 | 0.17 | 0.59 | 0.02 | 0.03 | 0.18 | 0.20 |
| ***office*** | ***large*** | ***Boston*** | 1.39 | 4.71 | 0.64 | 0.70 | 1.35 | 0.06 | 0.07 | 0.70 | 0.77 |
| ***health care*** | ***small*** | ***San Francisco*** | 0.54 | 3.23 | 0.46 | 0.43 | 1.68 | 0.06 | 0.08 | 0.52 | 0.52 |
| ***health care*** | ***large*** | ***San Francisco*** | 1.11 | 6.61 | 0.93 | 0.89 | 2.69 | 0.09 | 0.13 | 1.02 | 1.02 |
| ***lodging*** | ***small*** | ***San Francisco*** | 0.38 | 1.84 | 0.26 | 0.25 | 0.49 | 0.02 | 0.02 | 0.28 | 0.27 |
| ***lodging*** | ***large*** | ***San Francisco*** | 1.65 | 7.92 | 1.13 | 1.06 | 2.14 | 0.07 | 0.10 | 1.20 | 1.17 |
| ***office*** | ***small*** | ***San Francisco*** | 0.34 | 1.12 | 0.17 | 0.15 | 0.38 | 0.01 | 0.02 | 0.18 | 0.17 |
| ***office*** | ***large*** | ***San Francisco*** | 1.34 | 4.64 | 0.69 | 0.62 | 0.85 | 0.03 | 0.04 | 0.72 | 0.66 |

**Table 2. 2004 energy costs**

| | | *Atlanta* | | *Boston* | | *San Francisco* | |
|---|---|---|---|---|---|---|---|
| | | **summer** | **winter** | **summer** | **winter** | **summer** | **winter** |
| ***electricity*** | | | | | | | |
| **volumetric ($/kWh)** | *on-peak* | 0.061 | 0.061 | 0.082 | 0.069 | 0.165 | n/a |
| | *mid-peak* | 0.061 | 0.061 | n/a | n/a | 0.100 | 0.108 |
| | *off-peak* | 0.061 | 0.061 | 0.059 | 0.056 | 0.089 | 0.089 |
| **demand ($/kW)** | *on-peak* | n/a | n/a | n/a | n/a | 11.8 | na/ |
| | *mid-peak* | n/a | n/a | n/a | n/a | 2.65 | 2.65 |
| | *non-coincident* | n/a | n/a | 24.72 | 11.54 | 2.55 | 2.55 |
| **fixed fee ($/month)** | | 2750 | | 167 | | 175 | |
| ***natural gas*** | | | | | | | |
| **volumetric ($/kWh)** | | 0.037 | | 0.040 | | 0.032 | |
| **fixed fee ($/month)** | | 100 | | 100 | | 100 | |

source: Coughlin et al. (2005) and EIA (2007)

**Table 3. DER technology cost and performance**

| ***Discrete Investments*** | **fuel cell** | **microturbine** | | **reciprocating engine** | |
|---|---|---|---|---|---|
| **capacity (kW)** | 200 | 67 | 100 | 200 | 500 |
| **installed cost ($/kW)** | 5005 | 1826 | 1576 | 900 | 785 |
| **installed cost (EURO/kW)** | 6507 | 2374 | 2049 | 1170 | 1021 |
| **installed cost with heat recovery ($/kW)** | 5200 | 2082 | 1769 | 1250 | 1050 |
| **installed cost with heat recovery (EURO/kW)** | 6760 | 2707 | 2300 | 1625 | 1365 |
| **variable maintenance ($/kWh)** | 0.029 | 0.015 | 0.015 | 0.015 | 0.012 |
| **variable maintenance (EURO/kWh)** | 0.038 | 0.02 | 0.02 | 0.02 | 0.016 |
| **efficiency (LHV)** | 0.35 | 0.25 | 0.26 | 0.295 | 0.297 |
| **lifetime (a)** | 10 | 10 | 10 | 20 | 20 |

| ***Continuous Investments*** | **electrical storage** | **thermal storage** | **absorption chiller** | **solar thermal** | **photovoltaics** |
|---|---|---|---|---|---|
| **fixed cost ($)** | 295 | 10000 | 20000 | 15000 | 1000 |
| **fixed cost (EURO)** | 384 | 13000 | 26000 | 19500 | 1300 |
| **variable cost ($/kW or $/kWh)** | 193 | 200 | 115 | 150 | 4240 |
| **variable cost (EURO/kW or EURO/kWh)** | 251 | 260 | 150 | 195 | 5512 |
| **lifetime(a)** | 5 | 10 | 20 | 15 | 20 |

## Results

For each of the 18 buildings, a DER-CAM run is performed for carbon taxes ranging from $0/tC to $500/tC in increments of $50/tC. This is equivalent to a range of $0/tCO$_2$ to $182/tCO$_2$. For reference, CO$_2$ credits in the European Union Emission Trading Scheme peaked at approximately $110/tC (80 EURO/tC) or, equivalently, $39/tCO$_2$ (30 EURO /tCO$_2$) in April 2006. Figure 1 through Figure 3 plot the installed capacity of fossil-fuel fired generation, absorption cooling, solar thermal collection, respectively. Thermal storage was never purchased. Electrical storage and photovoltaics were only purchased in a handful of cases:

- Electrical storage- Boston, small lodging: ~130 kWh under all carbon tax levels
- Electrical storage- San Francisco, small office: ~17 kWh under all carbon tax levels
- Photovoltaics- San Francisco, small healthcare: 314 kW at $450/t and $500/t carbon tax levels
- Photovoltaics- San Francisco, large healthcare: 320 kW at $400/t carbon tax level, 612 kW at $450/t and $500/t carbon tax levels

Figure 4 plots carbon emissions under economically optimal DER investment as a fraction of no-invest emissions.

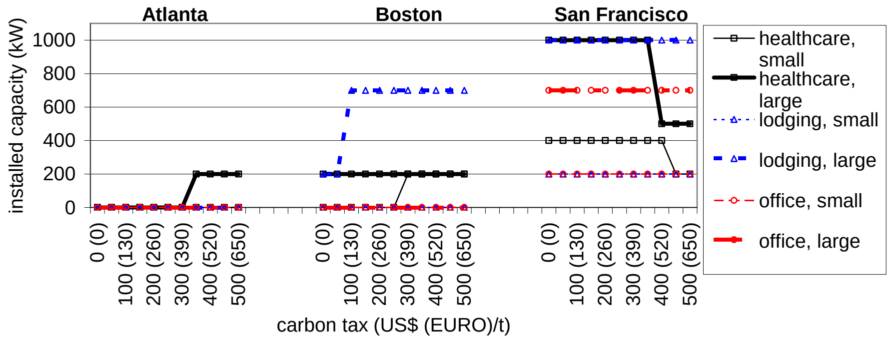

**Figure 1. installed capacity of CHP generators**

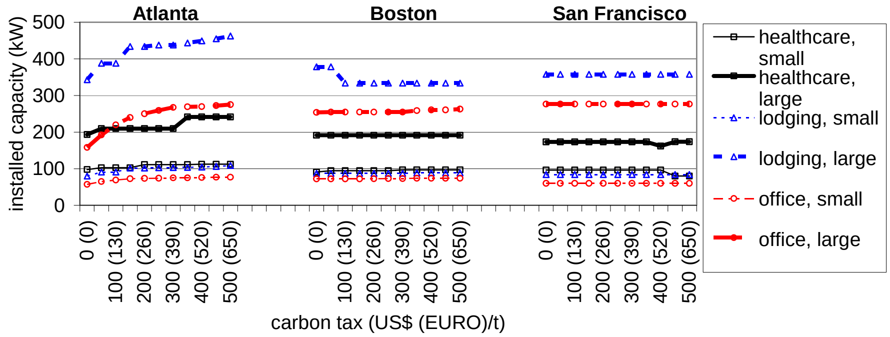

**Figure 2. installed capacity of absorption chillers**

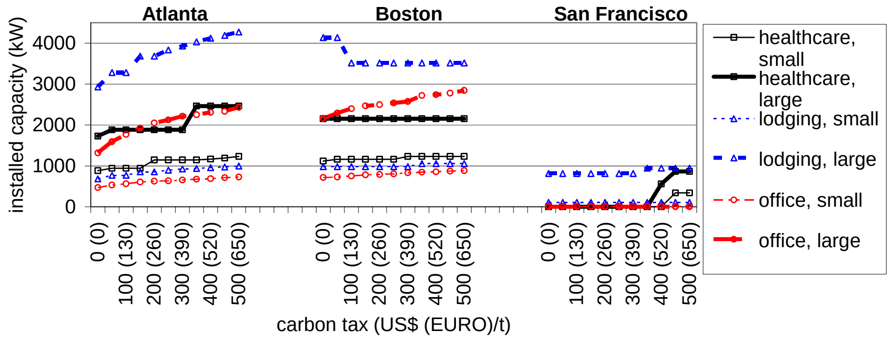

**Figure 3. installed capacity of solar thermal collectors**

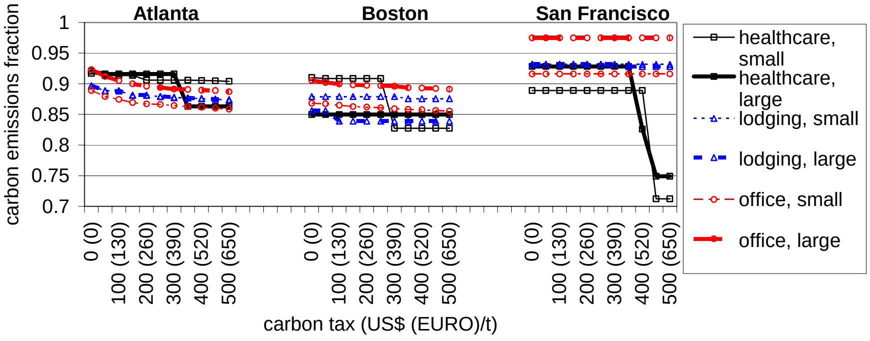

**Figure 4. site-attributable carbon emisisons as a fraction of no-invest carbon emissions**

## Conclusions

These results tell a different story for each of the three cities considered. In Atlanta, relatively low electricity prices do not incent CHP investment. However, solar thermal collectors coupled to absorption chillers are an economic approach to energy cost reductions, even without a carbon tax. As the carbon tax increases, larger solar collector/absorption chiller systems are chosen. At a realistic carbon tax level ($100/tC), however, carbon tax incents less than one percentage carbon reductions from the no-tax case.

In Boston, CHP is marginally economic; it is adopted at three sites, and in increasing quantities as the carbon tax increases. Solar thermal collectors coupled to absorption chillers are again economic. The size of these systems is not significantly affected by increasing carbon tax below an unrealistically high $300/tC. As in Atlanta, a realistic carbon tax level ($100/tC) incents less than one percentage carbon relative to the no-tax case.

In San Francisco, economic conditions are already ripe for commercial CHP – all six buildings considered would benefit financially from CHP, even without carbon taxes. Carbon emissions reductions from DER investment are slightly less than in Atlanta and Boston; relatively low electric grid marginal carbon emission and high electricity prices in California induce some carbon-inefficient behaviour, such as operating CHP when the heat is not needed. However, carbon taxes are not large enough to incent any different investment behaviour, except for health care sites at extremely high carbon taxes, which begin to invest in photovoltaics. Solar thermal collectors are not adopted in large capacities because the CHP systems provide the heat needed for the sites. Carbon taxes below $400/tC have an insignificant effect on carbon emissions.

Overall, the magnitude of a realistic carbon tax ($100/tC) is too small to incent significant carbon-reducing effects on economically optimal DER adoption. In large part, this is because 1) cost reduction and carbon reduction objectives are roughly aligned, even in the absence of a carbon tax and 2) a carbon tax greater than $500/tC would be required to incent significant adoption of carbon-free renewable energy.

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