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The Added Economic and Environmental Value of Solar Thermal Systems in Microgrids with Combined Heat and Power[1]

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ABSTRACT

The addition of solar thermal and heat storage systems can improve the economic, as well as environmental attraction of micro-generation systems, e.g. fuel cells with or without combined heat and power (CHP) and contribute to enhanced CO_2 reduction. However, the interactions between solar thermal collection and storage systems and CHP systems can be complex, depending on the tariff structure, load profile, etc. In order to examine the impact of solar thermal and heat storage on CO_2 emissions and annual energy costs, a microgrid's distributed energy resources (DER) adoption problem is formulated as a mixed-integer linear program. The objective is minimization of annual energy costs. This paper focuses on analysis of the optimal interaction of solar thermal systems, which can be used for domestic hot water, space heating and/or cooling, and micro-CHP systems in the California service territory of San Diego Gas and Electric (SDG&E). Contrary to typical expectations, our results indicate that despite the high solar radiation in southern California, fossil based CHP units are dominant, even with forecast 2020 technology and costs. A CO_2 pricing scheme would be needed to incent installation of combined solar thermal absorption chiller systems, and no heat storage systems are adopted. This research also shows that photovoltaic (PV) arrays are favored by CO_2 pricing more than solar thermal adoption.

INTRODUCTION

A microgrid is defined as a cluster of electricity sources and (possibly controllable) loads in one or more locations that are connected to the traditional wider power system, or

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macrogrid, but which may, as circumstances or economics dictate, disconnect from it and operate as an island, at least for short periods (see Microgrid Symposium 2005-2008, and Hatziargyriou et al. 2007). This paper focuses on the analysis of the optimal interaction of solar thermal systems, which can be used for domestic hot water, space heating and/or cooling, and micro-CHP systems with and without heat storage systems. In previous work, the Berkeley Lab has developed the Distributed Energy Resources Customer Adoption Model (DER-CAM), (Siddiqui et al. 2007, Stadler et al. 2008). Its optimization techniques find both the combination of equipment and its operation over a typical year that minimizes the site's total energy bill or CO_2 emissions,[2] typically for electricity plus natural gas purchases, as well as amortized equipment purchases. It outputs the optimal Distributed Generation (DG) and storage adoption combination and an hourly operating schedule, as well as the resulting costs, fuel consumption, and carbon emissions. Figure 1 shows a high-level schematic of the complex building energy flows as modeled in DER-CAM. Since finding the best economic or environmental solution is infeasible by trial-and-error searching, an analytic approach considering the whole set of possible technologies is necessary. To access the impact on solar thermal and absorption chiller adoption in 2020, medium sized (peak loads 100 kW to 5 MW) SDG&E territory buildings are investigated with DER-CAM.

2020 DER EQUIPMENT AND TARIFFS

The menu of available equipment options, their cost and performance characteristics, and the applicable SDG&E tariffs for this DER-CAM analysis are shown in Table 1, 2, and 3. Technology options in DER-CAM are categorized as either discretely or continuously sized. This distinction is important to the economics of DER because some equipment is subject to strong diseconomies of small scale. Continuously sized technologies are available in such a large variety of sizes that it can be assumed that close to optimal capacity could be implemented, e.g., storage. The installation cost functions for these technologies are assumed to consist of an unavoidable cost (intercept) independent of installed capacity that represents the fixed cost of the infrastructure required to adopt such a device, plus a variable cost proportional to

[2] In this work we always minimize the total energy bill.

capacity (see also Figure 2). As is typical for Californian utilities, the electricity tariff has time-of-use (TOU) pricing for both energy and power (demand charge). Demand charges are proportional to the maximum rate of electricity consumption (kW), regardless of the duration or frequency of such consumption over the billing period. The demand charge in $/kW is a significant determinant of technology choice and sizing of distributed generation and electric storage system installations (Stadler et al. 2008).

BUILDINGS ANALYZED

Lawrence Berkeley National Laboratory (LBL) is working with the California Energy Commission (CEC) to determine the role of DG and CHP in greenhouse gas reduction. The impact of DG at large industrial and commercial sites is well known, and their potential has largely already been harvested. In contrast, little is known about DG potential in medium-sized (peak loads 100 kW to 5 MW) commercial buildings. In this paper, 16 different building profiles[3] representing roughly 35% of SDG&E's commercial electricity demand are modeled using data from the California Commercial End-Use Survey (CEUS) database which contains 2790 premises total.

RESULTS

Four different runs were performed[4] and the results are shown in Table 4. The base case run does not consider any CO_2 pricing scheme and shows the dominance of internal combustion engines (ICE) with heat exchanger (HX) even in 2020. No solar thermal system is used to supply an absorption chiller.

In the CO_2 price run, a CO_2 price of \$123/tCO_2 increases the adopted solar thermal systems to approximately 77 MW and 53 MW are used in combination with absorption chillers. However, the CO_2 price also increases the number of installed fuel cells (FC) and reduces the number of ICE. The results in Table 4 also show that the medium CO_2 price favors PV systems.

To make solar thermal systems more attractive, a high absorption chiller coefficient of performance (COP) of 1.2 instead of the baseline 0.7 is used in the last two sensitivity

[3] hotels, hospitals, colleges, restaurants, warehouses, groceries, etc, in different sizes
[4] For all runs the average natural gas price between 2006 and 2008 is used as estimate for 2020, and therefore, this also considers the spike in natural gas prices in 2008.

runs. This results in increased solar thermal adoption and reduced PV adoption, but ICEs are still very dominant. The office building example from Figure 3 and 4 shows that cooling is necessary all day long and the absorption chiller is supplied by waste heat from CHP units as well as solar thermal during the day. This third case shows the highest CO_2 reduction (~31%) as well as annual energy bill saving (~22%) compared to a no-invest case[5] without any DG technologies. In the last run, a 30% investment subsidy[6] for heat storage is given and this brings heat storage into the solution. However, the study shows that most of the time non-solar thermal heat is used for charging (see Figure 5), and that due to cost minimization, the heat storage discharges even around noon hours.

CONCLUSIONS

The results show the dominance of internal combustion engines with HX, but also that solar thermal systems in combination with absorption chillers can facilitate the highest CO_2 emission reduction potential assuming a CO_2 pricing scheme. Additionally, in cases where cooling is needed all day long, most of the CO_2 reduction is already achieved by CHP units. When minimizing annual energy costs, heat storage does not directly support solar thermal / absorption chiller installations since storage is mostly charged by CHP units and sometimes discharged during productive solar thermal hours.

[5] Please note that the no-invest cases are not shown here and vary depending on the CO_2 price.
[6] Intercept costs for heat storage are set to zero.

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Figure 1. Schematic of the Energy Flow Model used in DER-CAM[7]

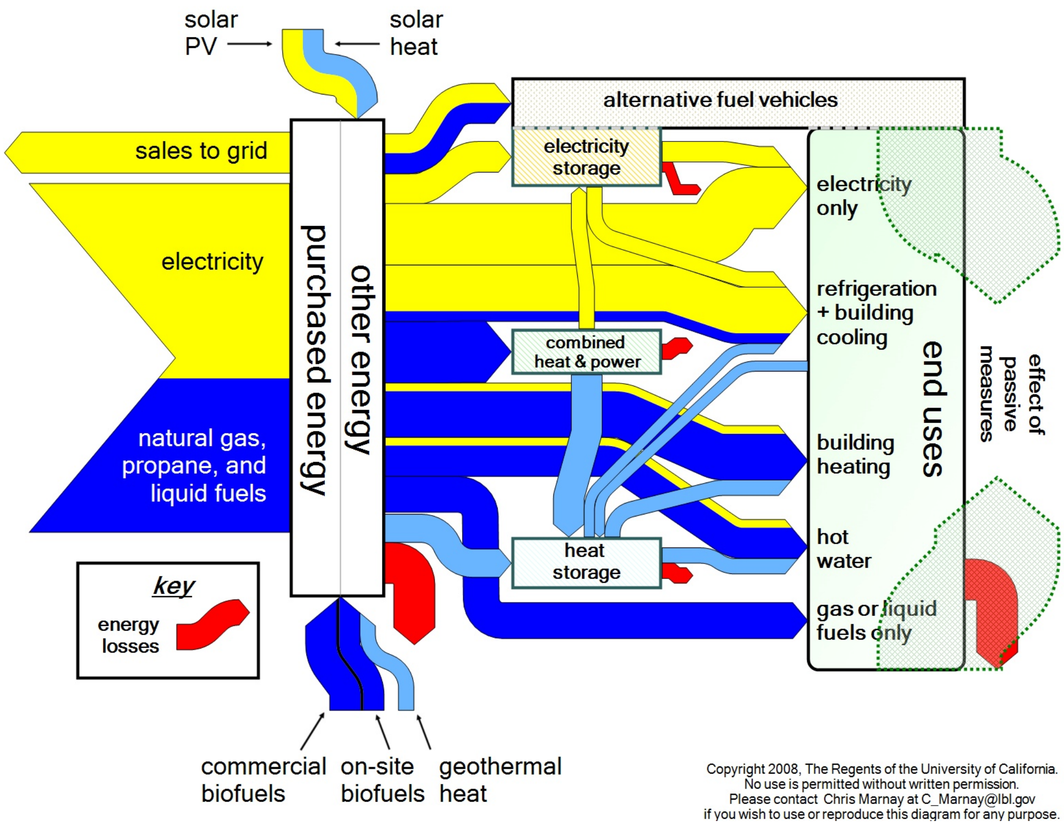
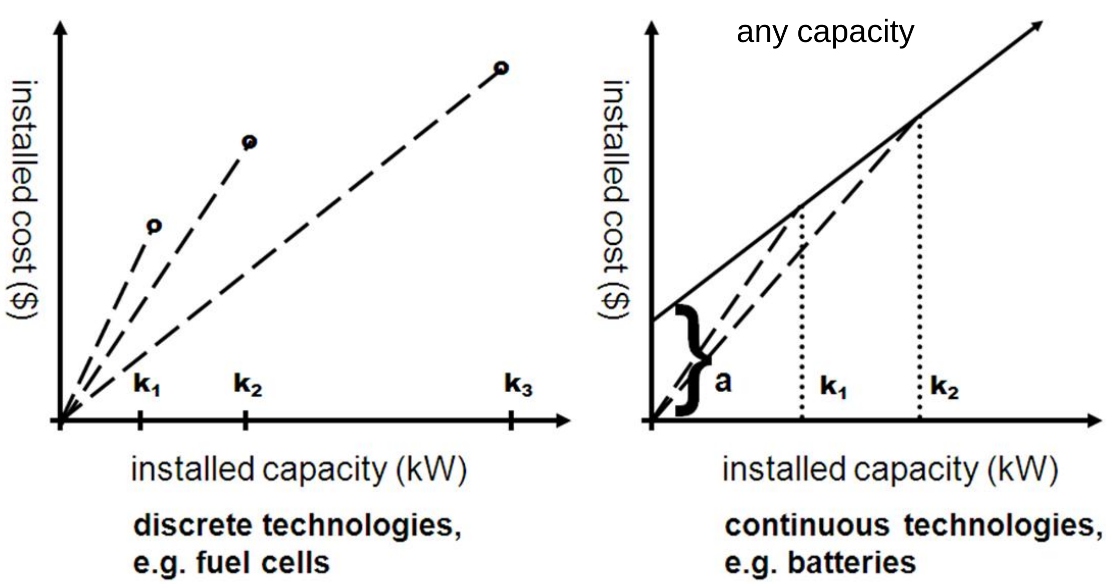


Figure 2. Discrete versus Continuous Technologies



[7] Please note that thermal storage contains also heat for absorption chillers, and therefore, Figure 1 considers cold thermal storage indirectly.

Table 1. Menu of Available Equipment Options in 2020, Discrete Investments

	capacity (kW)	installed costs (US$/kW)	installed costs with heat recovery (US$/kW)	variable maintenance (US$/kWh)	electric efficiency (%), (HHV)	lifetime (a)
ICE[8]-small	60	2721	na	0.02	0.29	20
ICE-med	250	1482		0.01	0.30	20
GT[9]	1000	1883		0.01	0.22	20
MT[10]-small	60	2116		0.02	0.25	10
MT-med	150	1723		0.02	0.26	10
FC[11]-small	100	2382		0.03	0.36	10
FC-med	250	1909		0.03	0.36	10
ICE-HX[12]-small	60	na	3580	0.02	0.29	20
ICE-HX-med	250		2180	0.01	0.30	20
GT-HX	1000		2580	0.01	0.22	20
MT-HX-small	60		2377	0.02	0.25	10
MT-HX-med	150		1936	0.02	0.26	10
FC-HX-small	100		2770	0.03	0.36	10
FC-HX-med	250		2220	0.03	0.36	10
MT-HX-small-wSGIP[13]	60		2217	0.02	0.25	10
MT-HX-med-wSGIP	150		1776	0.02	0.26	10
FC-HX-small-wSGIP	100		2270	0.03	0.36	10
FC-HX-med-wSGIP	250		1720	0.03	0.36	10

Sources: Goldstein et al. 2003, Firestone 2004, SGIP 2008, own calculations

[8] ICE: Internal combustion engine
[9] GT: Gas turbine
[10] MT: Microturbine
[11] FC: Fuel cell
[12] HX: Heat exchanger. Technologies with HX can utilize waste heat for heating or cooling purposes.
[13] wSGIP: Considers the California self generation incentive program, which is basically an investment subsidy.

Table 2. Menu of Available Equipment Options in 2020, Continuous Investments

	thermal storage	absorption chiller	solar thermal	photo-voltaics
intercept costs (US$)	10000	93912	1000	3851
variable costs (US$/kW or US$/kWh)	100 US$/kWh	685 US$/kW[14]	500 US$/kW	3237 US$/kW
lifetime (a)	17	20	15	20

Sources: Firestone 2004, EPRI-DOE Handbook 2003, Mechanical Cost Data 2008, SGIP 2008, own calculations

Table 3. Estimated SDG&E Commercial Energy Prices in 2020

Electricity	Summer (May – Sep.)		Winter (Oct. – Apr.)	
	electricity (US$/kWh)	**demand (US$/kW)**	**electricity (US$/kWh)**	**demand (US$/kW)**
non-coincident	na	12.80	na	12.80
on-peak	0.13	13.30	0.13	4.72
mid-peak	0.11		0.12	
off-peak	0.08		0.09	
fixed (US$/month)	232.87/58.22[15]			

Natural Gas	
0.03	US$/kWh
112.18/ 11.22[16]	fixed (US$/month)

Source: SDG&E Tariffs and own calcualtions

summer on-peak: 11:00 – 18:00 during weekdays
summer mid-peak: 06:00 – 11:00 and 18:00 – 22:00 during weekdays
summer off-peak: 22:00 – 06:00 during weekdays and all weekends and holidays
winter on-peak: 17:00 – 20:00 during weekdays
winter mid-peak: 06:00 – 17:00 during weekdays
winter off-peak: 20:00 – 06:00 during weekdays and all weekends and holidays

[14] In kW electricity of an equivalent electric chiller.
[15] Customers with an electric peak load above 500kW pay $232.87/month. Customers with an electric peak load less than 500kW pay $58.22/month.
[16] Customers with a natural gas consumption above 615,302 kWh/month pay $112.18/month. Customers with a natural gas consumption less than 615,302 kWh/month pay $11.22/month.

Table 4. Major Results for SDG&E Service Territory

Results	base case (no CO_2 price)	CO_2 price	CO_2 price, high COP	CO_2 price, high COP, cheap heat storage
adopted solar thermal (MW)	3	77	344	346
solar thermal for absorption cooling (MW)	0.0	53	302	277
adopoted heat storage (MWh)	0.0	0.0	0.0	432
adopted PV (MW)	73	495	356	278
adopted FC with HX (MW)	0.0	63	12	29
adopted ICE with HX (MW)	462	354	445	422
annual electricity displaced due to absorption building cooling (GWh/a)	350	196	582	596
annual energy bill savings compared to the no-invest[17] case (M$)	129	186	226	225
annual energy bill savings compared to the no-invest case (%)	17	17	22	23
annual total CO_2 emission reduction compared to the no-invest case (ktCO2/a)	350	777	818	774
annual total CO_2 emission reduction compared to the no-invest case (%)	13	30	31	30

[17] Please note that the no-invest cases are not shown here and vary depending on the CO_2 price.

Figure 3. Diurnal Electricity Pattern of a Medium Office Building for a July Weekday, Medium CO2 Price, High COP of 1.2

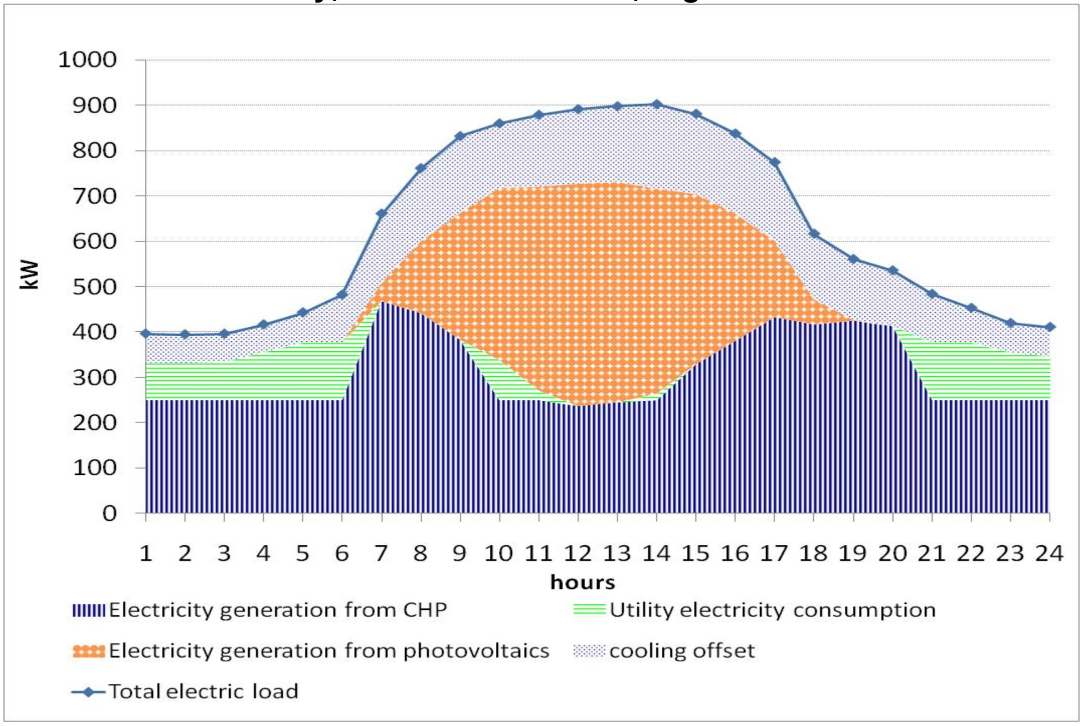


Figure 4. Diurnal Heat Pattern of a Medium Office Building for a July Weekday, CO_2 Price, High COP of 1.2

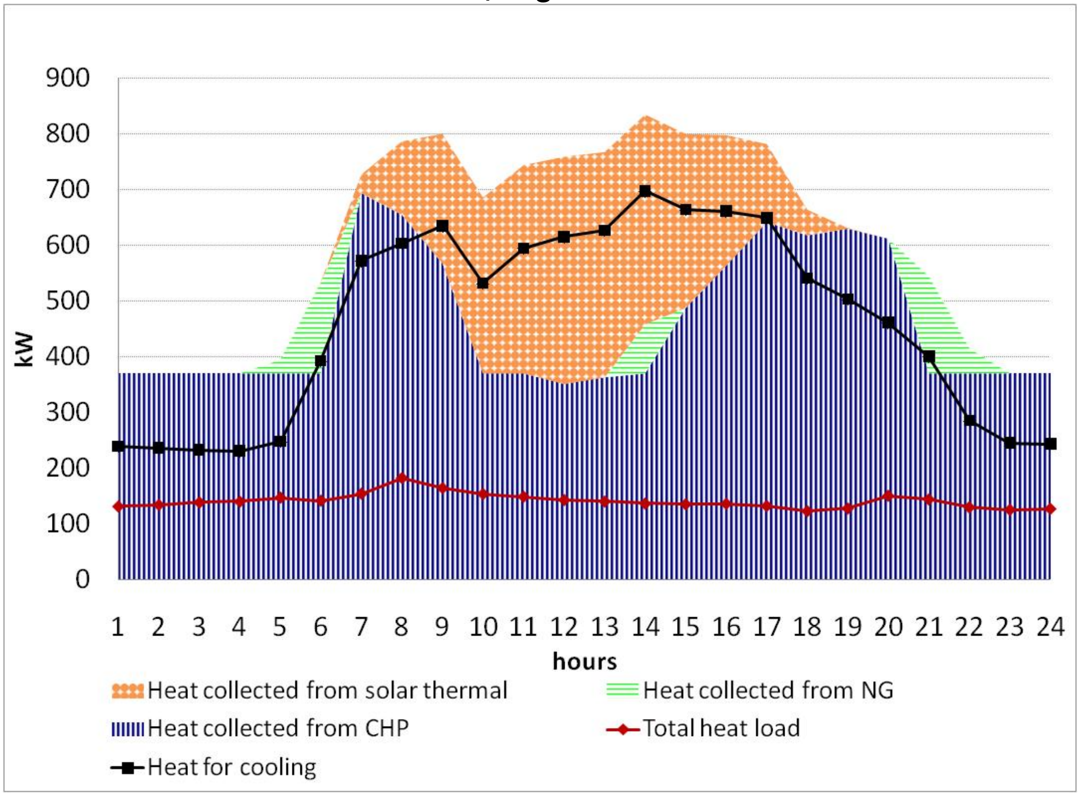


Figure 5. Diurnal Heat Pattern of a Medium Office Building for a July Weekday, CO_2 Price, High COP of 1.2, Cheap Heat Storage