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ABSTRACT

The addition of storage technologies such as lead-acid batteries, flow batteries, or heat storage can potentially improve the economic and environmental attractiveness of on-site generation such as PV, fuel cells, reciprocating engines or microturbines (with or without CHP), and can contribute to enhanced demand response. Preliminary analyses for a Californian nursing home indicate that storage technologies respond effectively to time-varying electricity prices, i.e. by charging batteries during periods of low electricity prices and discharging them during peak hours. While economic results do not make a compelling case for storage, they indicate that storage technologies significantly alter the residual load profile, which may lower carbon emissions as well as energy costs depending on the test site, its load profile, and DER technology adoption.

Introduction

In this paper, a microgrid is defined as a cluster of electricity sources and (possibly controllable) loads at one or more locations that are connected to the traditional wider power system, or macrogrid, but which may, as circumstances or economics dictate, disconnect from it and operate as an island, at least for short periods (Hatziargyriou, N. et al. 2007). The Berkeley Lab has developed the Distributed Energy Resources

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Customer Adoption Model (DER-CAM), (Siddiqui et al. 2003, Stadler et al. 2006). Its optimization techniques find both the combination of equipment and its operation over a typical year to minimize the site's total energy bill, typically for electricity and natural gas purchases, as well as amortized equipment costs. The latest version also includes storage technologies such as regular batteries (e.g. lead-acid batteries), flow batteries as well as heat storage.

The Distributed Energy Resources - Costumer Adoption Model (DER-CAM)

DER-CAM (Siddiqui et al. 2003) is a mixed-integer linear program (MILP) written and executed in the General Algebraic Modeling System (GAMS®). Its objective is to minimize the annual costs for providing energy services to the modeled site, including utility electricity and natural gas purchases, amortized capital, and maintenance costs for distributed generation (DG) investments. It outputs the optimal 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 energy flow as modeled in DER-CAM.

Optimal combinations of equipment involving PV, thermal generation with heat recovery, thermal heat collection, and heat-activated cooling can be identified in a way that would be intractable by trial-and-error enumeration of possible combinations. The economics of storage are particularly complex, both because they require optimization across multiple time steps and because they are heavily influenced by complex tariff structures (on-peak, off-peak, demand charges, etc.). Note that facilities with on-site generation will incur electricity bills more biased toward demand (peak power) charges and less toward energy charges, thereby making the timing and control of chargeable peaks of particular operational importance.

DER Equipment Including Storage Technologies

The menu of available equipment options to DER-CAM for this analysis together with their cost and performance characteristics are shown in Tables 1, 2, and 3. While the current set of available technologies is limited in this analysis, any candidate technology may potentially be included.

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. battery storage. The installation cost functions for these technologies are assumed to consist of an unavoidable cost (intercept) independent of installed capacity representing the fixed cost of the infrastructure required to adopt such a device, plus a variable cost proportional to capacity.

Results

The northern Californian nursing home is the first of several California and New York being studied. The home has a peak total electrical load of 958 kW. Table 4 shows its local Pacific Gas and Electric (PG&E) rates. Carbon emission intensities of purchased electricity and natural gas from PG&E are assumed to be 140 g/kWh (marginal value) and 49 g/kWh, respectively. Six DER-CAM runs were performed: 1. a *do nothing* case in which all DER investment is disallowed, i.e., the nursing home meets its local energy demands solely by purchases; 2. an *invest* case, which finds the optimal DER investment; 3. a *low storage and PV price*; 4. to assess the value of storage systems, a run was performed forcing the same investments as run 3, but with storage disallowed; 5. a *low storage, PV, and solar thermal price* run; and 6. a *low storage price and 60% PV price reduction/subsidy* run.

The number of installed Tecogen® reciprocating engine stays constant in all performed runs because CHP is attractive to this site because of the coincidence of heat and electric loads. DER-CAM also provides an optimal schedule for each installed technology, which is illustrated using the low storage cost runs 3 and 6 (Figure 2 to 4). Note that since electric cooling loads can be offset by the absorption chiller, there are

four possible ways to meet cooling loads: utility purchases of electricity, on-site generation of electricity, absorption chiller offsets, and stored electricity in batteries.
At the assumed price levels, neither electric nor thermal storage is economically attractive (see run 2). Including low-cost storage of US$50/kWh for solar thermal and US$60/kWh for electric storage lowers annual operating costs by almost 5% (see run 3); however, the elemental carbon reduction is only ca. 12% meaning that elemental carbon emission reduction is lower with the adoption of electric and thermal storage than without it (run 2). This finding is proven by run 4, which forces the same results as in the low storage cost run 3, but prohibits storage adoption. The major driver for electric storage adoption is the objective to reduce energy costs, and this can be effectively reached by avoiding electricity consumption during on-peak hours. Batteries are charged by cheap off-peak electricity and displaces utility consumption during on-peak hours (see also Figure 3). Assuming the same marginal carbon emission rate during on- and off-peak hours results in additional carbon emissions (efficiency losses); however, as shown in run 6 (see Table 5), the combination of PV and electrical storage brings together the positive economic effects of batteries with the positive environmental effects of PV.

Conclusions

The results show a wide range in the complexity of optimal systems but fairly similar costs and diverse carbon emissions. Heat, electric load profile, tariff structure, available solar insolation, and installed DG equipment all have strong effects on the site's achievable energy cost and carbon abatement. The demand charge is a significant driver for the adoption of electric storage technologies and so storage is discharged during productive PV hours, raising carbon emissions overall.

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Figure 1. Schematic of DER-CAM

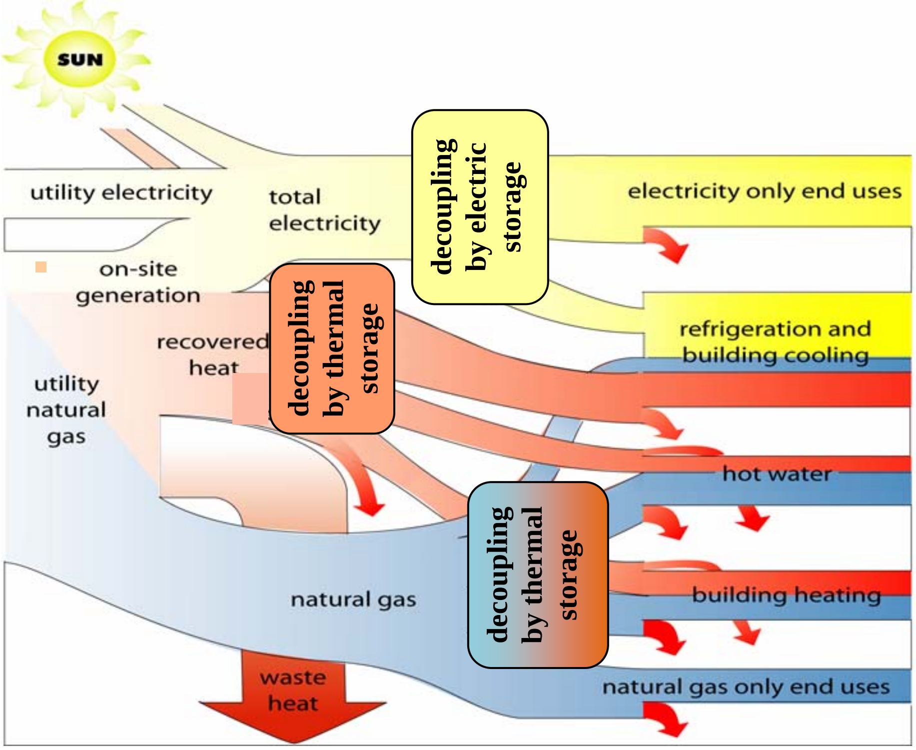

Table 1. Energy Storage Parameters

	description	**electrical**	**flow battery**	**thermal**
charging efficiency (1)	portion of energy input to storage that is useful	0.9	0.84	0.9
discharging efficiency (1)	portion of energy output from storage that is useful	1	0.84	1
decay (1)	portion of state of charge lost per hour	0.001	0.01	0.01
maximum charge rate (1)	maximum portion of rated capacity that can be added to storage in an hour	0.1	n/a	0.25
maximum discharge rate (1)	maximum portion of rated capacity that can be withdrawn from storage in an hour	0.25	n/a	0.25
minimum state of charge (1)	minimum state of charge as apportion of rated capacity	0.3	0.25	0

Table 2. Menu of Available Equipment Options, *Discrete Investments*.

	reciprocating engine	**fuel cell**
capacity (kW)	100	200
sprint capacity	125	☒
installed costs (US$/kW)	2400	5005
installed costs with heat recovery (US$/kW)	3000	5200
variable maintenance (US$/kWh)	0.02	0.029
efficiency (%), (HHV)	26	35
lifetime (a)	20	10

Table 3. Menu of Available Equipment Options, *Continuous Investments*

	electrical storage	**thermal storage**	**flow battery**	**absorption chiller**	**solar thermal**	**photo-voltaics**
intercept costs (US$)	295	10000	0	20000	1000	1000
variable costs (US$/kW or US$/kWh)	193 US$/kWh	100 US$/kWh	220 US$/kWh / 2125 US$/kW	127 US$/kW	500 US$/kW	6675 US$/kW
lifetime (a)	5	17	10	15	15	20

Table 4. Commercial Energy Prices (source: PG&E, effective Nov 2007)

Electricity	**Summer (May – Oct.)**		**Winter (Nov. – Apr.)**	
	electricity (US$/kWh)	**demand (US$/kW)**	**electricity (US$/kWh)**	**demand (US$/kW)**
on-peak	0.16	15.04		
mid-peak	0.12	3.58	0.12	1.86
off-peak	0.09		0.10	
fixed (US$/day)	9.04			

Natural Gas	
0.04	US$/kWh
4.96	fixed (US$/day)

summer on-peak: 12:00 – 18:00 during weekdays
summer mid-peak: 08:00 – 12:00 and 18:00 – 22:00 during weekdays
summer off-peak: remaining hours and days
winter mid-peak: 08:00 – 22:00 during weekdays;

Table 5. Annual Results for the Northern California Nursing Home

	run 1	run 2	run 3	run 4	run 5	run 6
	do nothing	invest in all technologies	low storage costs and PV incentive of 2.5US$/W	force low storage / PV results	low storage costs and PV incentive of 2.5US$/W & low solar thermal costs (minus 10% of original costs)	low storage costs and 60% PV price reduction
equipment						
Tecogen 100 kW with heat exchanger (kW)	n/a	300	300	300	300	300
abs. Chiller (kW in terms of electricity)		48	46	46	85	40
solar thermal collector (kW)		134	109	109	443	43
PV (kW)		0	0	0	0	517
electric storage (kWh)		0	4359	n/a	4148	2082
thermal storage (kWh)		0	123	n/a	196	47
annual total costs (kUS$)						
total	964	926	916	926	915	910
% savings compared to do nothing	n/a	3.94	4.98	3.94	5.08	5.60
annual elemental carbon emissions (t/a)						
emissions	1088	945	960	946	944	834
% savings compared to do nothing	n/a	13.14	11.76	13.05	13.24	23.35

Figure 2. Jan. Weekday low Storage and PV Price (run 3) Diurnal Heat Pattern

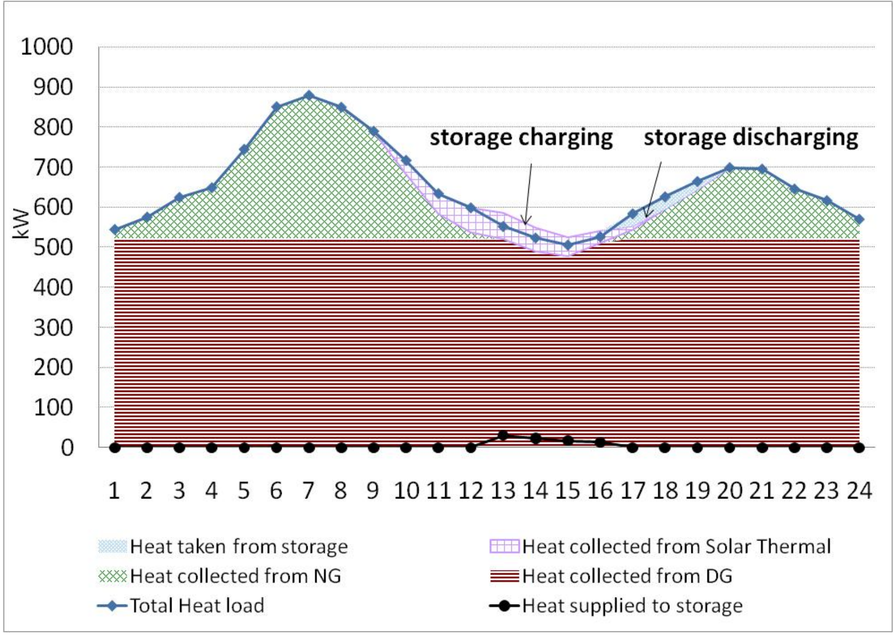

Figure 3. Jul. Weekday low Storage and PV Price (run 3) Diurnal Elec. Pattern

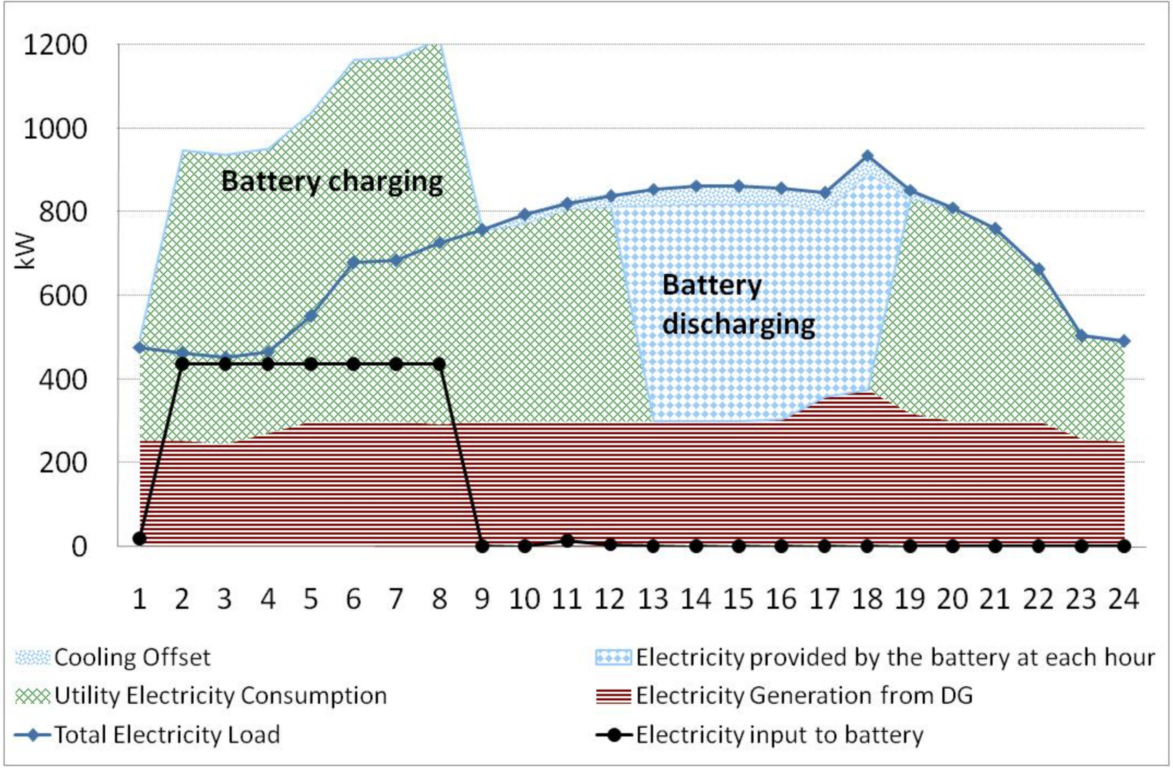

Figure 4. Jul. Weekday low Storage Price and 60% PV Price Reduction (run 6) Diurnal Elec. Pattern