Integrated building energy systems design considering storage technologies

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Abstract

The addition of storage technologies such as flow batteries, conventional batteries, and heat storage can improve the economic, as well as environmental attraction of micro-generation systems (e.g. PV or fuel cells with or without CHP) and contribute to enhanced demand response. The interactions among PV, solar thermal, and storage systems can be complex, depending on the tariff structure, load profile, etc. In order to examine the impact of storage technologies on demand response and CO_2 emissions, a microgrid's distributed energy resources (DER) adoption problem is formulated as a mixed-integer linear program that can pursue two strategies as its objective function. These two strategies are minimization of its annual energy costs or of its CO_2 emissions. The problem is solved for a given test year at representative customer sites, e.g. nursing homes, to obtain not only the optimal investment portfolio, but also the optimal hourly operating schedules for the selected technologies. This paper focuses on analysis of storage technologies in micro-generation optimization on a building level, with example applications in New York State and California. It shows results from a two-year research project performed for the U.S. Department of Energy and ongoing work. Contrary to established expectations, our results indicate that PV and electric storage adoption compete rather than supplement each other considering the tariff structure and costs of electricity supply. The work shows that high electricity tariffs during on-peak hours are a significant driver for the adoption of electric storage technologies. To satisfy the site's objective of minimizing energy costs, the batteries have to be charged by grid power during off-peak hours instead of PV during on-peak hours. In contrast, we also show a CO_2 minimization strategy where the common assumption that batteries can be charged by PV can be fulfilled at extraordinarily high energy costs for the site.

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 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, 2006, and Hatziargyriou et al. 2007). The successful deployment of microgrids will depend heavily on the economics of distributed energy resources (DER) in general, and upon the early success of small clusters of mixed technology generation, grouped with storage, and controllable loads. If clear economic, environmental, and utility system benefits from such early projects are realized, momentum can propel the adoption of added microgrid capabilities as well as precipitate the regulatory adjustments necessary to allow widespread microgrid introduction.

The potential benefits of microgrids are multi-faceted, but from the adopters' perspective, there are two major groupings: 1) the cost, efficiency, and environmental benefits (including possible emissions credits) of combined heat and power (CHP), and 2) the power quality and reliability (PQR) benefits of on-site generation and control. At the same time, it should be noted that growth in electricity demand in developed countries centers on the residential and commercial sectors in which

CHP applications particularly have not hitherto been well developed.

This paper reports on the latest efforts intended to insert CO_2 minimization, as well as storage (both electrical and thermal), capabilities into the microgrid analysis on a building level. In previous work, the Berkeley Lab has developed the Distributed Energy Resources Customer Adoption Model (DER-CAM), (Siddiqui et al. 2003). Its optimization techniques find both the combination of equipment and its operation over a typical year that minimize the site's total energy bill or CO_2 emissions, typically for electricity plus natural gas purchases, as well as amortized equipment purchases. The chosen equipment and its schedule should be economically attractive to a single site or to members of a microgrid consisting of a cluster of sites, and it should be subsequently analyzed in more engineering and financial detail (Stadler et al. 2006).

A common assumption in the scientific community is that photovoltaic (PV) and batteries can supplement each other and contribute to less CO_2 emissions since renewable energy could be stored in the battery and used during night hours. We will pay special attention to that assumption and show that it is a very rough assumption and that it neglects important economic boundaries. Additionally, current piece meal practices in system design are not very useful to find the optimal solution. The energy flows in a building are complex enough that it is not possible to find the best economic as well as environmental solution by trial-and-error approaches, and therefore, integrated approaches that consider the whole set of possible technologies are necessary. Thus, to access the impact on storage, PV, as well as solar thermal system adoption, two nursing homes, one in the San Francisco Bay Area and one in NYC are investigated with DER-CAM.

The Distributed Energy Resources – Customer Adoption Model (DER-CAM)

DER-CAM (Stadler et al. 2008) is a mixed-integer linear program (MILP) written and executed in the General Algebraic Modelling System (GAMS). Its objective is to minimize the annual costs or CO_2 emissions for providing energy services to the modelled site, including utility electricity and natural gas purchases, amortized capital and maintenance costs for distributed generation (DG) investments. The approach is fully technology-neutral and can include energy purchases, on-site conversion, both electrical and thermal on-site renewable harvesting, and end-use efficiency investments[1]. Furthermore, the system choice considers the simultaneity of the building cooling problem; that is, results reflect the benefit of displacement of electricity demand by heat-activated cooling that lowers building peak load and, therefore, the generation requirement.

Site-specific inputs to the model are end-use energy loads[2], electricity and natural gas tariff structure and rates, and DG investment options. The following technologies are currently considered in the DER-CAM model:[3]

- natural gas-fired reciprocating engines, gas turbines, microturbines, and fuel cells;
- photovoltaics and solar thermal collectors;
- electrical storage, flow batteries, and heat storage;
- heat exchangers for application of solar thermal and recovered heat to end-use loads;
- direct-fired natural gas chillers; and
- heat-driven absorption chillers.

Figure 1[4] shows a high-level schematic of the energy flow modelled in DER-CAM. Available energy inputs to the site are solar insolation, utility electricity, utility natural gas, biofuels, and geothermal heat. For a given site, DER-CAM selects the economically or environmental optimal combination of utility electricity purchase, on-site generation, storage and cooling equipment, required to meet the site's following end-use loads at each time step:

- electricity-only loads, e.g. lighting and office equipment;
- cooling loads that can be met either by electricity powered compression or by heat activated absorption cooling, direct-fired natural gas chillers, waste heat or solar heat;
- hot-water and space-heating loads that can be met by recovered heat or by natural gas;
- natural gas-only loads, e.g. mostly cooking that can be met only by natural gas.

In this paper the complete set of loads for a representative full care 24 hour nursing facility with five floors and a total area of 31,587 m^2 (340,000 sq. ft) was obtained from the California Energy Commission (CEC) and the California Commercial End-Use Survey (CEUS).

The outputs of DER-CAM include the optimal DG and storage adoption and an hourly operating schedule, as well as the resulting costs, fuel consumption, and CO_2 emissions (Figure 2).

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 of the influence of tariff structures (on-peak, off-peak, and demand charges). 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.

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[1] End-use efficiency investments, which are currently under design, are not considered in this paper (see also Marnay 2008 and Stadler 2008b).

[2] Three different day-long profiles are used to represent the set of daily profiles for each month: weekday, peak day, and weekend day. DER-CAM assumes that three weekdays of each month are peak days.

[3] Despite the wide variety of technologies considered in DER-CAM, we use a subset of technologies in this work to keep the results clear. See also section "DER Equipment Including Storage Technologies".

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

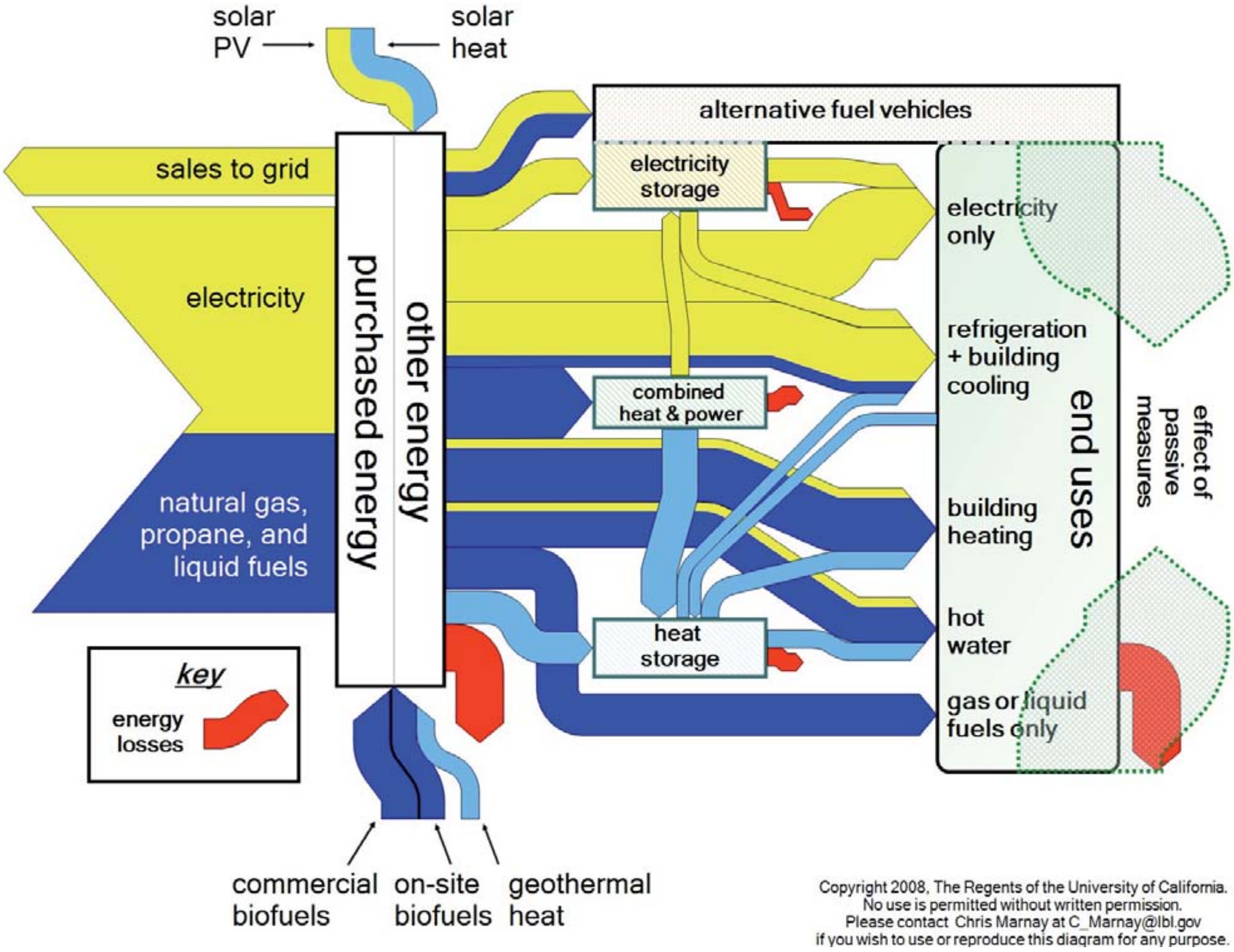


Figure 1. Schematic of the Energy Flow Model used in DER-CAM

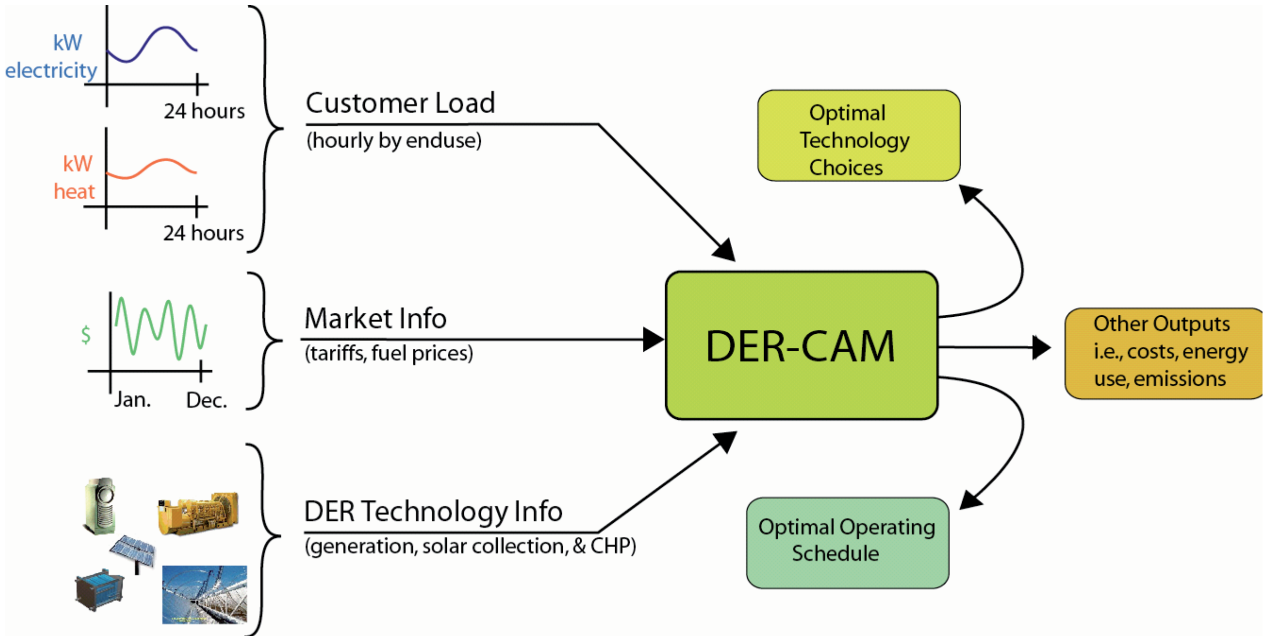
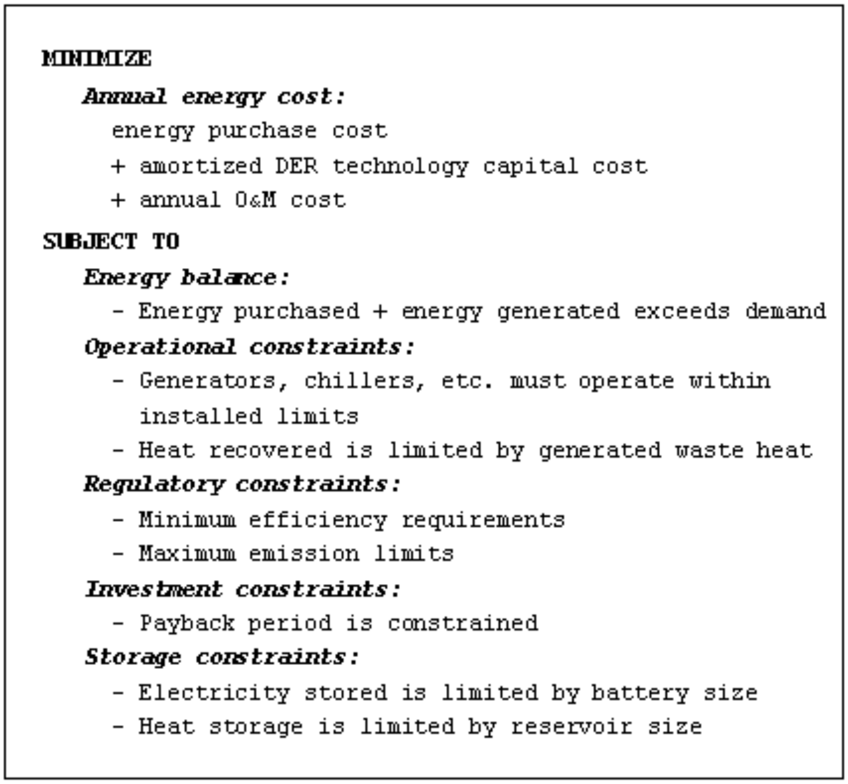


Figure 2. High-Level Schematic of Information Flow in DER-CAM



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MINIMIZE
    Annual energy cost:
      energy purchase cost
      + amortized DER technology capital cost
      + annual O&M cost
SUBJECT TO
    Energy balance:
      - Energy purchased + energy generated exceeds demand
    Operational constraints:
      - Generators, chillers, etc. must operate within
        installed limits
      - Heat recovered is limited by generated waste heat
    Regulatory constraints:
      - Minimum efficiency requirements
      - Maximum emission limits
    Investment constraints:
      - Payback period is constrained
    Storage constraints:
      - Electricity stored is limited by battery size
      - Heat storage is limited by reservoir size
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Figure 3. MILP Solved by DER-CAM

One major feature is currently under design and not yet used in this paper. To make DER-CAM more complete and holistic a demand-side-management (DSM) module is currently under design. As can be seen from Figure 1 the end uses can be directly influenced by efficiency measures and demand reduction measures. Please note that batteries act as load shifting measures, and therefore, they are considered in this paper. For more preliminary information on the DSM module see Marnay 2008 or Stadler 2008b.

The MILP solved by DER-CAM is shown in 'pseudo-code' in Figure 3[5]. In minimizing the site's objective function, DER-CAM also has to take into account various constraints. Among these, the most fundamental ones are the energy-balance and operational constraints, which require that every end-use load has to be met and that the thermodynamics of energy production and transfer are obeyed. The storage constraints are essentially inventory balance constraints that state that the amount of energy in a storage device at the beginning of a time period is equal to the amount available at the beginning of the previous time period plus any energy charged, minus any energy discharge, minus losses. Finally, investment and regulatory constraints may be included as needed. A limit on the acceptable simple payback period is imposed to mimic typical investment decisions made in practice. Only investment options with a payback period less than 12 years are considered for this paper. For a complete mathematical formulation of the MILP with energy storage solved by DER-CAM, please refer to Stadler et al. 2008.

DER Equipment Including Storage Technologies[6]

This paper reports results using electrical, i.e. a conventional lead/acid battery, and thermal storage, capabilities, with both electrical and thermal storage being viewed as inventories. At each hour, energy can either be added (up to the maximum capacity) or withdrawn (down to a minimum capacity chosen to avoid damaging deep discharge). The rate at which the state of charge can change is constrained, and the state of charge decays hourly. The parameters used for the electrical and thermal storage models are shown in Table 1 (see also Stevens et al. and Symons et al.).

The menu of available equipment options to DER-CAM for this analysis together with their cost and performance characteristics is shown in Tables 2 and 3.

While the current set of available technologies is limited, any candidate technology may 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. Discretely sized technologies are those that would be available to customers only in a limited number of discrete sizes, and DER-CAM must choose an integer number of units, e.g. reciprocating engines. Please note that both continuous and discrete technologies exhibit economies of scale, but the discrete ones can be more complex and dramatic. Additionally, considering storage technologies as continuous types does improve the performance of DER-CAM. The costs for the discrete

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[5] Not all constraints are shown (e.g. flow batteries have more different constraints than regular electric storage).

[6] Only active storage systems are considered. No thermal effects of the building shell are taken into account at this point.

Table 1. Energy Storage Parameters

	description	electrical	flow battery$^{I)}$	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$^{II)}$	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

I) Flow batteries differ from conventional rechargeable batteries in one significant way: the power and energy ratings of a flow battery are independent of each other. This is made possible by the separation of the electrolyte and the battery stack. Flow batteries can be rapidly ‘recharged’ by replacing the electrolyte liquid stored in an external tank.

II) Please note that our decay factor is relatively high due to the fact that the lifetime of lead acid batteries is assumed at the upper end of the lifetime range. At the end of the lifetime the decay increases rapidly. Additionally, the decay increases at higher temperature. However, future investigations will address the impact of different decay factors.

Table 2. Menu of Available Equipment Options, Discrete Investments

	reciprocating engine	fuel cell
capacity (kW)	100	200
sprint capacity	125	╳
installed costs ($/kW)	2400	5005
installed costs with heat recovery ($/kW)	3000	5200
variable maintenance ($/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	photovoltaics
intercept costs ($)	295	10000	0	20000	1000	1000
variable costs ($/kW or $/kWh)	$193^{III)}$	$100^{IV)}$	$220 / 2125^{V)}$	$127^{VI)}$	$500^{VII)}$	$6675^{VIII)}$
lifetime (a)	5	17	10	15	15	20

III) $\$/kWh_{electricity}$

IV) $\$/kWh_{heat}$

V) Flow batteries are characterized by both the energy content and power rating.

VI) abs. chiller capacity is in terms of electricity offset (electric load equivalent).

VII) $\$/kW_{of\ recovered\ heat}$

VIII) $\$/kW_{electricity}$

fuel cell[7] technology are interpolated from various studies as described in (Firestone 2004), which is based on data collected by the National Renewable Energy Laboratory (Goldstein et al. 2003). The costs and performance data for the reciprocating engine are based on data provided by Tecogen. Continuously sized technologies are available in such a large variety of sizes that it can be assumed capacity close to the optimal could be acquired, e.g. battery storage, the costs for which are roughly consistent with those described by the Electricity Storage Association (see also Electricity Storage Association). The installation cost functions for these technologies are assumed to consist of an unavoidable cost (intercept) independent of installed capacity ($) representing the fixed cost of the infrastructure required to adopt such a device, plus a variable cost proportional to capacity ($/kW or $/kWh).[8]

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[7] Reciprocating engines are the most dominant technologies. Research shows that no fuel cell or micro turbine adoption takes place in our examples due to higher costs.

[8] Regarding Table 3: Please note that cold thermal storage is not among the set of available technologies, but could be added.

Results

The newest version of DER-CAM can be used to minimize the annual total costs, the annual CO_2 emissions of the micro-generation system or combinations of them, i.e. multi-objective function. Depending on the considered objective, the investment portfolio and operation schedule of the installed technologies can change considerably. To show the impact of the chosen objective on the storage technology as well as PV and solar thermal adoption, two different strategies / objectives are shown in the following sections.

COST MINIMIZATION STRATEGY OF THE MICRO-GENERATION SYSTEM

Optimal DER Equipment for a Northern California Nursing Home

A numerical example was completed for a northern California nursing home in the San Francisco Bay Area operating during 2007. This facility has a peak total electrical load of 958 kW. The nursing home has a very stable seasonal heat and electric load with high heating loads during the night and morning hours. Additionally, during the daytime hours, heat can be used to lower the electrical peak. When cooling demand increases, this can constitute a stable heat sink if waste heat for absorption chillers is considered. Finally, the electricity demand coincides with the total heat demand and this favors the installation of DG units with CHP. The simultaneous use of heating and cooling is caused by a) the complexity of nursing facilities where heating and cooling can appear in different zones at the same time and b) hot water loads (see also Figure 4).

Table 4 shows the prices used, which are based on local Pacific Gas and Electric (PG&E) rates. Natural gas prices for the region were also obtained from PG&E tariffs. A marginal CO_2 emission factor of 513 g/kWh for electricity purchased from PG&E was assumed (Marnay et al. 2002). Finally, the CO_2 emission factor for each DG unit is calculated by dividing the natural gas CO_2 emission factor of 180 g/kWh by the appropriate higher heating value (HHV) efficiency. For example, the CO_2 emission factor is 692 g/kWh for the 100 kW reciprocating engine. From the data, DER is not necessarily more energy or carbon efficient than central station power. For example, simple cycle on-site generation of electricity using reciprocating engines at this site would be more carbon intensive than procurement from PG&E; however, using waste heat to offset thermal or electrical loads can improve the overall carbon efficiency.

- Summer on-peak: 12:00-18:00 during weekdays,
- Summer mid-peak: 08:00-12:00 and 18:00-22:00 during weekdays, all other hours and days: off-peak;
- Winter mid-peak: 08:00-22:00 during weekdays, all other hours and days: off-peak;

In order to address how CO_2 emissions and total site energy costs change when electric and thermal storage is present, five DER-CAM runs are shown: 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 at current technology costs; 3. a *low storage and PV cost* run with variable storage costs of \$50/kWh for thermal and \$60/kWh for electric storage, as well as a \$2.5/W PV incentive[9]; 4. to assess the value of storage systems, a run was performed forcing the same investments as in the low storage price run 3, but in which storage is disallowed; and 5. a *low storage cost and 60% PV variable cost reduction* run[10].

The major results for these five runs are shown in Table 5. In the *do-nothing* case (run 1), the nursing home meets all of its electricity demand via utility purchases and burns natural gas to meet all of its heating requirements. The annual operating cost is \$964,000 (741,538 Euro[11]), and 3989 t of CO_2 are emitted each year. In the *invest* case (run 2) technology parameters from Table 1, 2, and 3 are used and DER-CAM finds the optimal system. The optimal system for the site consists of three Tecogen gas engines, a 48 kW absorption chiller, and a 134 kW solar thermal system. At current price levels, neither electric nor thermal storage is economically attractive. Relative to the *do-nothing* case, the expected annual savings for the optimal DER system are \$38000/a (ca. 4%) while the CO_2 emissions reduction is 524 t/a (ca. 13%). Considering low storage prices of \$50/kWh for thermal and \$60/kWh for electric storage, as well as \$2.5/W PV incentive, the annual operating costs drop by almost 5% (see run 3). However, the CO_2 reduction is only ca. 12%. This means that the CO_2 emission reduction is lower with adoption of electric and thermal storages 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 disallows storage adoption. The major driver for electric storage adoption is the objective to reduce energy costs, and this can be very effectively reached by avoiding electricity consumption during on-peak hours. In this example, the battery is charged by very cheap off-peak electricity and displaces utility consumption during on-peak hours[12], (see also Figure 6). The results for run 3 show increased electricity consumption due to charging / discharging inefficiency and decay. Assuming the same marginal CO_2 emission rate during on-peak and off-peak hours results in additional CO_2 emissions.

However, as shown in run 5, the combination of PV and electrical storage brings together the positive economic effects of batteries with the positive environmental effects of PV. The annual operating costs drop by 5.60% while the CO_2 emission reduction is 23.35% compared to the *do-nothing* case run 1. However, part of the battery capacity is replaced by direct PV usage as indicated in Figure 7 and PV is not used for battery charging.

Another important finding for the nursing home is that the number of installed Tecogen reciprocating engines stays constant in all performed runs. The reason for this is the CHP favorable heat and electricity load (see also Figure 4). High electricity demand combined with high heat demand makes CHP very attractive.

It should be noted that these results are estimated assuming perfect reliability of DER equipment. Imperfect reliability would mostly affect the demand charges, but would also have other effects on the value of the project, e.g. on the standby

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[9] Intercept costs are set to \$0.

[10] Intercept costs are set to \$0 again.

[11] Exchange rate of \$1.3 per Euro as of January 12, 2009.

[12] Flow batteries are never chosen, and therefore, omitted in Table 5.

Table 4. Input Energy Prices effective Nov. 2007

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

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

Sources: PG&E commercial tariffs, PG&E tariffs, PG&E commercial, and PG&E natural gas tariffs.

Table 5. Annual Results for the Northern California Nursing Home, using Cost Minimization within DER-CAM

	run 1	run 2	run 3	run 4	run 5
	do-nothing	invest in all technologies	low storage costs and PV incentive of 2.5$/W	force low storage / PV results	low storage costs and 60% PV cost reduction
equipment					
reciprocating engine, Tecogen 100 kW with heat exchanger (kW)	n/a	300	300	300	300
abs. Chiller (kW in terms of electricity)		48	46	46	40
solar thermal collector (kW)		134	109	109	43
PV (kW)		0	0	0	517
electric storage (kWh)		0	4359	n/a	2082
thermal storage (kWh)		0	123	n/a	47
annual total costs (k$)					
total	964	926	916	926	910
% savings compared to do nothing	n/a	3.94	4.98	3.94	5.60
annual energy consumption (GWh)					
electricity	5.76	3.23	3.33	3.22	2.40
NG	5.70	9.99	10.00	10.03	10.10
annual CO_2 emissions (t/a)					
emissions	3989	3465	3520	3469	3058
% savings compared to do nothing	n/a	13.14	11.76	13.05	23.35

charge as back up to DER would have to be provided by the utility.

Besides the optimal investment plan, DER-CAM provides the microgrid with an optimal schedule for each installed technology, which we illustrate using the low storage cost run 3 and run 6 (see Figures 5 through 7). 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.

Optimal DER Equipment for a New York City Nursing Home

The same CA nursing home was transferred to Consolidated Edison Company of New York (ConEd) service territory in NYC to investigate the impact of different tariffs on technology adoption. To consider the impact of the colder winter and hotter summer climate the load profiles were adjusted by temperature data. This transformation provides the impact of different tariffs and higher heating loads. However, additional case studies show that the most important influencing factor is the tariff. More information can be found in Stadler et al. 2008.

For the New York City nursing home, the prices in Table 6 were used.

A marginal CO_2 emission factor of 733 g/kWh for electricity purchased from ConEd was assumed (see also Cadmus 1998).

A major difference for the NYC sites is the almost flat electricity tariff ($/kWh) and the seasonal demand charge ($/kW). This circumstance translates directly into a lower incentive to avoid on-peak power/energy consumption. Additionally, the 23% higher natural gas price ($/kWh) in NYC compared to PG&E service territory has a negative influence on ICE installations and no Tecogen unit is selected by DER-CAM.

In the *do-nothing* case (run 1), the nursing home meets all of its electricity demand via utility purchases and burns natural gas to meet all of its heating requirements. The annual operating cost is $1,196,000 (920,000 Euro [13]), and 5702 t of CO_2 are emitted each year.

The optimal system for the site consists of a 100 kW absorption chiller[14] and a 1438 kW solar thermal system. At current

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[13] Exchange rate of 1.3$ per Euro as of January 12, 2009.

[14] In terms of electricity equivalent of a reference electric chiller with a COP of 4.5.

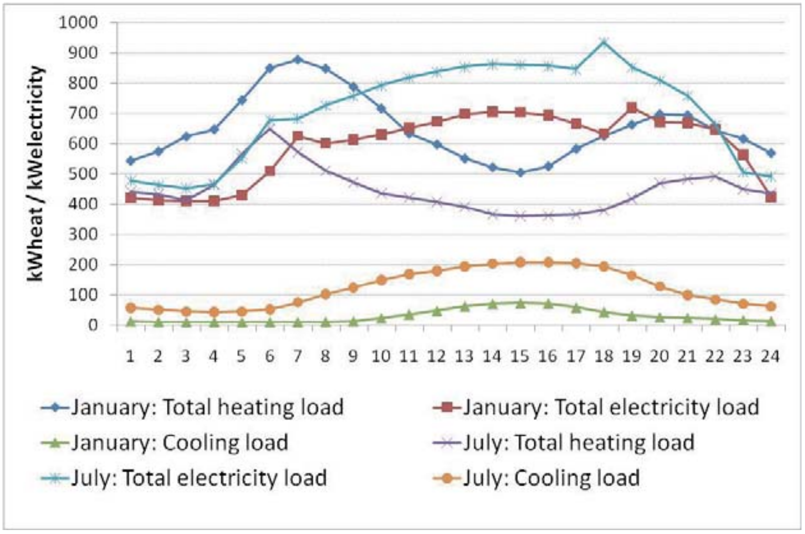

Figure 4. Total Heat and Electricity Demand for the CA Nursing Home on January and July Weekdays

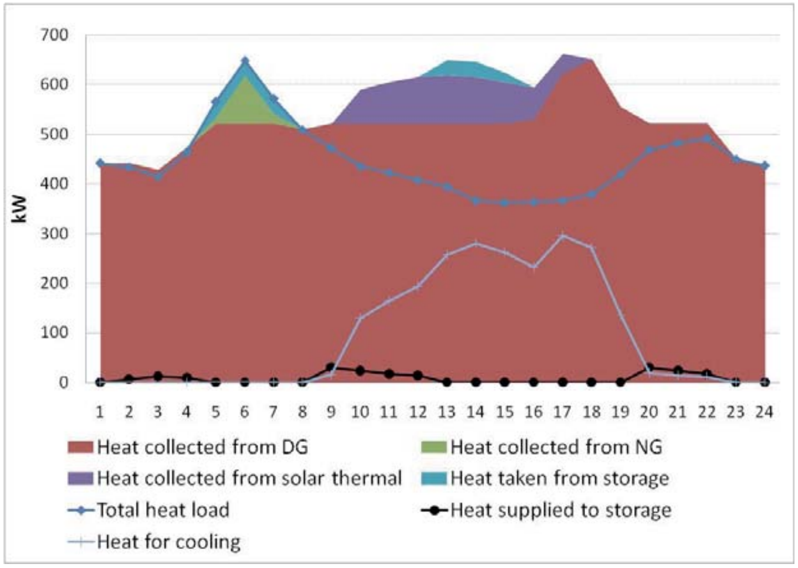

Figure 5. Low Storage and PV Price (run 3) Diurnal Heat Pattern for the CA Nursing Home on a July Weekday

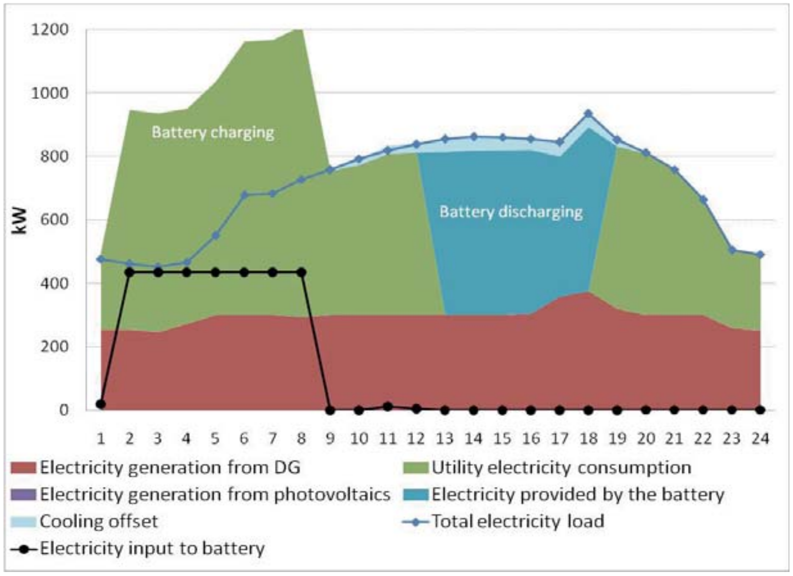

Figure 6. Low Storage and PV Price (run 3) Diurnal Electricity Pattern for the CA Nursing Home on a July Weekday

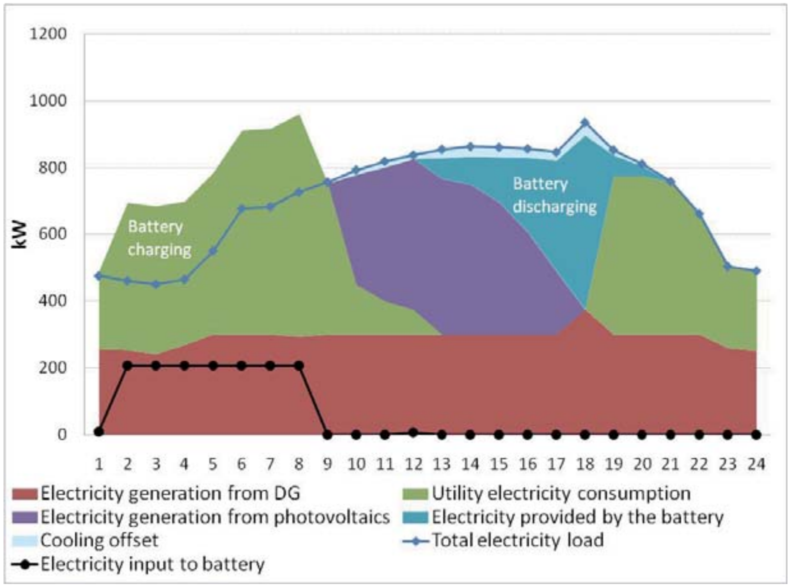

Figure 7. Low Storage Price and 60% PV Price Reduction (run 5) Diurnal E. Pattern for the CA Nursing Home on a July Weekday

Table 6. Energy Prices, effective April 2007

electricity	summer (June – Sep.)		winter (Oct. – May)	
	electricity ($/kWh)	**demand ($/kW)**	**electricity ($/kWh)**	**demand ($/kW)**
all day long	0.12[IX)]	14.21[X)]	0.12	11.36[XI)]
fixed ($/month)	71.05			

natural gas	
0.049	$/kWh
0.419	fixed ($/day)

Source: ConEd

IX) Please note that there is a slight monthly variation in the electricity price depending on the market supply charge and monthly adjustment clause. However, these adjustments do not follow regular monthly patterns and are unpredictable. The variation for the observed year was between 0.10 and 0.13$/kWh.
X) For the first 300 kW. If the load exceeds 300 kW the demand charge decreases by 10%
XI) For the first 300 kW. If the load exceeds 300 kW the demand charge decreases by 12%

Table 7. Annual Results for the NYC Nursing Home, using Cost Minimization within DER-CAM

	run 1	run 2	run 3	run 4	run 5
	do-nothing	invest in all technologies	low storage costs and PV incentive of 2.5$/W	force low storage / PV results	low storage costs and 60% PV cost reduction
equipment					
reciprocating engine, Tecogen 100 kW with heat exchanger (kW)	n/a	0	0	0	0
abs. Chiller (kW in terms of electricity)		100	112	112	112
solar thermal collector (kW)		1438	2350	2350	2350
PV (kW)		0	0	0	0
electric storage (kWh)		0	294	n/a	294
thermal storage (kWh)		0	4862	n/a	4862
annual total costs (k$)					
total	1196	1161	1149	1179	1149
% savings compared to do nothing	n/a	2.93	3.92	1.42	3.92
annual energy consumption (GWh)					
electricity	6.02	5.90	5.95	5.82	5.95
NG	7.14	5.24	3.50	4.82	3.50
annual CO_2 emissions (t/a)					
emissions	5702	5276	4990	5141	4990
% savings compared to do nothing	n/a	7.46	12.46	9.84	12.46

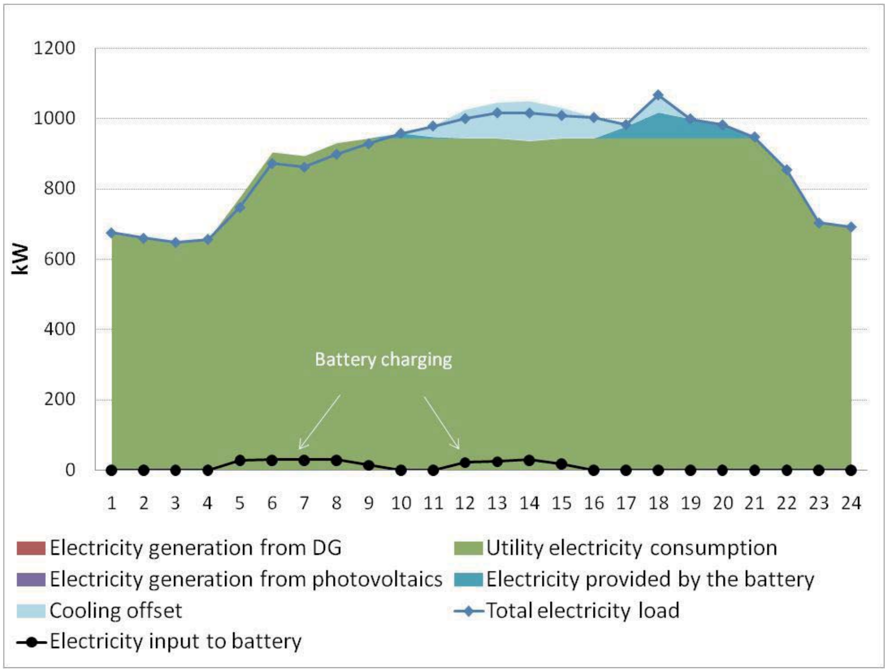

Figure 8. Low Storage & PV Price (run 3) Diurnal Electricity Pattern for the NYC Nursing Home on a July Weekday)

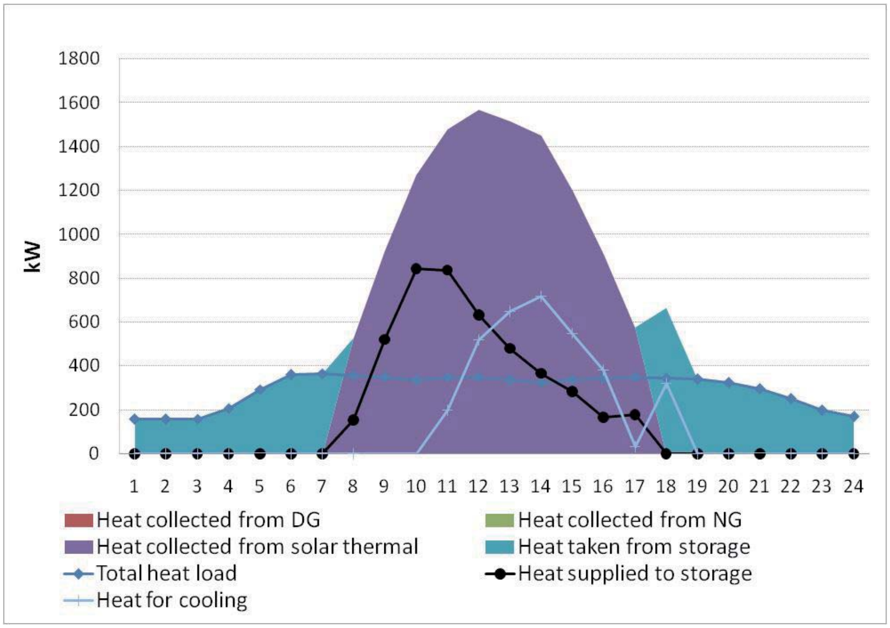

Figure 9. Low Storage and PV Price (run 3) Diurnal Heat Pattern for the NYC Nursing Home on a July Weekday

price levels, electrical storage, thermal storage, PVs, and ICEs are all economically unattractive. Relative to the *do-nothing* case, the expected annual savings for the optimal DER system is $35,000/a (ca. 2.9%) while the CO_2 emission reduction is 425 t/a (ca. 7.5%). Considering the lower NYC solar radiation compared to California, the installation of the huge solar thermal system is very surprising. It seems that the high heating demand combined with the absence of DG-CHP units compensates for the lower solar radiation.

Applying lower storage prices, the annual operating costs drop by almost 4% and the CO_2 reduction is ca. 12.5%. In contrast to the CA nursing home, the adoption of electrical and thermal storage improves the environmental benefits (see also run 3). This finding is proven by run 4, which forces the same results as in the *low storage cost* run 3, but disallows storage adoption. What is so different about the NYC nursing home that causes it to show a completely different pattern? It is the absence of electrical storage and the presence of a big thermal storage system. The flat high electricity tariff of $0.12/kWh

Table 8. Annual Results for the Northern California Nursing Home, using the CO_2 Minimization Objective within DER-CAM

	run 1	run 2	run 3	run 4	run 5
	do-nothing	invest in all technologies	low storage costs and PV incentive of 2.5$/W	force low storage / PV results	low storage costs and 60% PV cost reduction
equipment					
reciprocating engine, Tecogen 100 kW with heat exchanger (kW)	n/a	400	400	400	400
abs. Chiller (kW in terms of electricity)		0	0	0	0
solar thermal collector (kW)		2198	2197	2197	2192
PV (kW)		2957	2958	2958	2959
electric storage (kWh)		16274	16276	n/a	16287
thermal storage (kWh)		10811	10805	n/a	10775
annual total costs (k$)					
total	964	2972	1760	1867	1371
% savings compared to do nothing	n/a	-208	-83	-94	-42,18
annual energy consumption (GWh)					
electricity	5.76	0.39	0.39	1.68	0.38
NG	5.70	2.88	2.89	7.25	2.90
annual CO_2 emissions (t/a)					
emissions	3989	720	720	2177	720
% savings compared to do nothing	n/a	82	82	45	82

prevents almost all electrical storage adoption. The installed battery capacity here is only ca. 7% of the installed battery capacity of the CA nursing home. The reduced battery capacity also reduces the CO_2 emissions related to battery inefficiencies. Additionally, the big solar thermal system in combination with the huge thermal storage system contributes to the positive environmental effect. The adopted thermal storage system is 39.5 times bigger than in the California nursing home case.[15]

Figure 8 shows a further important impact of the flat electricity tariff: the battery is almost equally charged by off-peak and on-peak times. This shows impressively the power of TOU tariffs on the battery charge/discharge cycle.

Finally, Figure 9 shows the heat pattern. During the summer months, the heat storage is used excessively to provide domestic hot water.

Considering low storage prices and lowest PV prices (run 5), no difference to run 3 is reached and PV is not attractive.

CO_2 MINIMIZATION STRATEGY OF THE MICRO-GENERATION SYSTEM

As shown in the section before, the major driver for electric storage adoption is a TOU tariff and a high demand charge. However, the CA example shows that even with PV costs less than 60% of today's prices electric storage systems are charged by cheap off-peak electricity and not by PV (see Figure 7). Additionally, storage inefficiencies result in less carbon reduction potential with electric storage adoption compared to the case without storage. This problem gets even worse considering the fact that the off-peak power plant might be coal and substitute "clean" on-peak natural gas plants. In other words, considering also the costs for electricity supply batteries are more in a competition with PV than to help each other as shown by the CA example.

Thus, is the common assumption that batteries help PV penetration entirely wrong? To answer that question we also did runs for the nursing home with a CO_2 minimization strategy instead of a cost minimization strategy. This new objective function will deliver a different adoption pattern.

Optimal DER Equipment for a Northern California Nursing Home

As before, five different runs were performed and the results of the runs are shown in Table 8. Most importantly, the CO_2 emissions can be reduced by 82% compared to the *do-nothing* case. However, since investment costs and operational costs are not important due to the used CO_2 minimization strategy, the annual bill increases dramatically. For run 2, with actual technology costs, the annual total costs are lifted by more than 200%. As can be seen from Table 8, huge PV, solar thermal as well as storage systems will be adopted. To limit PV and solar thermal adoption an area constraint of 30,000 m^2, which represents the total floorspace area of the five story urban building, was used within DER-CAM[16]. Also, comparing Table 8 with Table 5 re-

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[15] Flow batteries are never chosen, and therefore, omitted in Table 6.

[16] The 30,000 m^2 constraint might be high, but shows how important the area constraint is. Assuming an average efficiency of 0.5 for solar thermal and 0.13 for PV results to 27,142 m^2. In other words, reducing the area constraint to e.g. 6,000 m^2 will reduce the adopted PV and solar thermal. A trivial conclusion is that there might be not enough space in urban areas to accomplish zero carbon buildings by PV or solar thermal only (Marnay 2009). A sensitivity run for *the invest in all technologies* case with an area constraint of 6,000 m^2 results to a 60% CO_2 reduction.

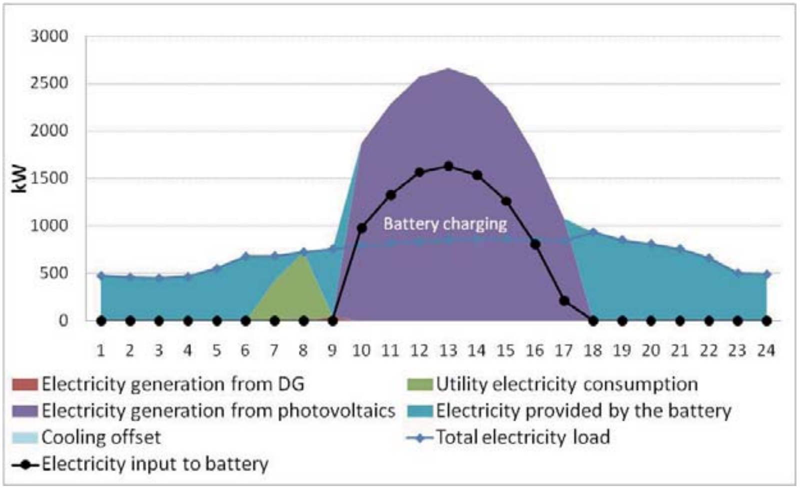

Figure 10. Low Storage and PV Price (run 3) Diurnal Electricity Pattern for the CA Nursing Home on a July Weekday, CO_2 Minimization

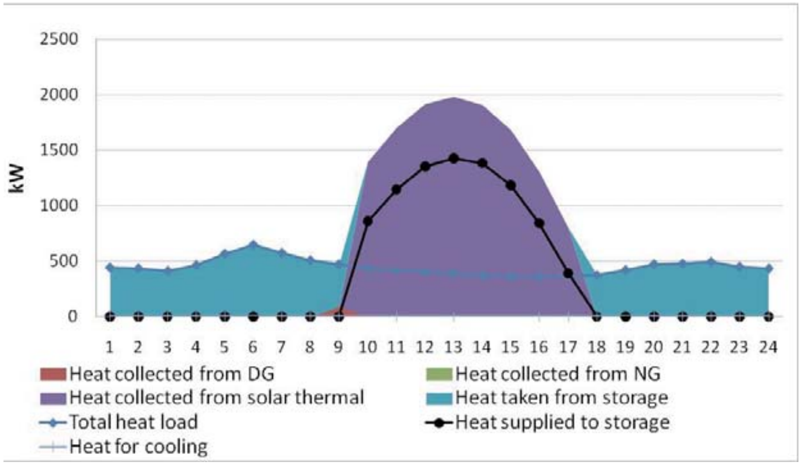

Figure 11. Low Storage and PV Price (run 3) Diurnal Heat Pattern for the CA Nursing Home on a July Weekday, CO_2 Minimization

veals that a CO_2 minimization strategy, without considering costs, can result in a bigger ICE system than in the case with cost minimization. Thus, CO_2 minimization does not necessarily reduce the adopted ICE equipment. In this case it results in less usage of the ICE equipment since costs are not important.

However, one critical note needs to be made in accordance with the absent DSM options within DER-CAM. It is obvious that a building manager would implement efficiency programmes also to bring costs down. In other words, in reality no one will be that concerned about CO_2 emissions to pay the above posted annual total bill. There might be a lot of efficiency measures or demand response measures to reduce loads and avoid supply by little-used ICE engines. This is the reason why a newer version of DER-CAM is under development, which can also consider efficiency measures in the optimization (Marnay 2008 and Stadler 2008b).

However, neglecting energy costs and focusing entirely on CO_2 emissions leads to the common assumption that PV and batteries can supplement each other and reduce the environmental impact as demonstrated by run 3 and 4 in Table 8. Disallowing storage systems in run 4 and forcing DER-CAM to install the same supply technologies as in run 3 results in less carbon reduction potential. The storage inefficiencies are not important in these cases since the storage systems are entirely charged by PV or solar thermal during the day (see also Figure 10 and 11).

Conclusions

In this paper two objective functions, i.e. cost minimization versus CO_2 minimization are applied to a nursing home using electrical and thermal storage capabilities. The DER-CAM results show a wide range in the complexity of optimal systems and the effects on annual total costs and CO_2 emissions.

One major conclusion from this research is that load profiles, tariff structure and available solar radiation have an enormous impact on the site's achievable energy cost as well as carbon emission reduction. Almost every run, in combination with the tariff structure and its objective function, is unique. The results are often complex and it would not be possible to find the optimal solution with just a trial and error approach. Specifically, storage poses a difficult problem because any decision made in any one time period must consider the effects on all other time periods. These circumstances make an integrated and holistic approach, as provided by DER-CAM, necessary.

Both traditional batteries, such as the familiar lead-acid types, and flow batteries are considered. When available at approximately their estimated current full cost and considering cost minimization, no storage technologies are chosen for any of the test sites, and the same is true for PV. The sensitivity runs show that PV is never used to charge battery systems. Therefore, to satisfy the site's objective of minimizing energy costs, the batteries have to be charged by grid power during off-peak hours instead of PV during on-peak hours. This circumstance, combined with storage inefficiencies, results in slightly higher carbon emissions for the nursing homes than omitting storage. As shown by the comparison of the California and New York examples in this research, the demand charge reduction is a significant driver for the adoption of electric storage technologies. The PG&E tariff consists of time-of-use tariffs for both electricity ($/kWh) and demand ($/kW), which encourages load management by batteries. However, the high electric demand during on-peak hours, which coincide with the solar radiation, results in peak shaving by the battery and PV. The CA nursing home makes considerable grid electricity purchases over the course of the day, but buys virtually nothing during the on-peak period, 12:00-18:00. The engines, the PV, and the batteries are all used to avoid afternoon grid purchase. In other words, the batteries are used to save cheap off-peak electricity for consumption during the expensive on-peak hours; therefore, the PV and the batteries are in competition to provide this service. The New York nursing home exhibits a completely different pattern. First of all, the adopted battery capacity is only ca. 7% of the installed battery capacity of the CA nursing home and then the charge / discharge cycle is completely different due to the absence of time-of-use tariffs – the batteries are charged between 04:00 and 16:00.

However, a different objective function of the microgrid, i.e. CO_2 minimization can result in considerable battery charging by renewable energy sources, i.e. PV that compensates for the storage inefficiencies. To demonstrate that behaviour the CA nursing home was optimized using the CO_2 minimization strategy. Neglecting energy costs and focusing entirely on CO_2 emissions leads to the common assumption that PV and batteries can supplement each other and reduce the environmental impact considerably. The storage inefficiencies are not important in this case since the storage systems are entirely charged by PV or solar thermal during the day. However, this strategy can result in annual total costs for the nursing home which are more than 200% higher than in the *do-nothing* case where all energy is supplied by the macrogrid. However, it is obvious that a building manager would first implement efficiency programs also to bring costs down. In other words, in reality no one will be that concerned about CO_2 emissions to pay 200% higher annual total bills. There might be a lot of efficiency or demand response measures to reduce loads. This is the reason why a newer version of DER-CAM, which can also consider efficiency measures in the optimization, is currently under development and being tested.

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