## Title

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## Permalink

https://escholarship.org/uc/item/0rk8w586

## Journal

Energy and Buildings, 40(4)

## ISSN

0378-7788

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## Publication Date

2008

## DOI

10.1016/j.enbuild.2007.04.005

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ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect

Energy and Buildings 40 (2008) 537–548

ENERGY and BUILDINGS

www.elsevier.com/locate/enbuild

# Integration of distributed generation systems into generic types of commercial buildings in California

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Received 5 March 2007; received in revised form 25 March 2007; accepted 13 April 2007

## Abstract

Distributed generation (DG) of combined cooling, heat, and power (CCHP) has been gaining momentum in recent years as an efficient, secure alternative for meeting increasing power demands in the world. One of the most critical and emerging markets for DG-CCHP systems is commercial and institutional buildings. The present study focuses analysis on the main economic, energy-efficiency, and environmental impacts of the integration of three types of advanced DG technologies (high-temperature fuel cells, micro-turbines, and photovoltaic solar panels) into four types of representative generic commercial building templates (small office building, medium office building, hospital, and college/school) in southern California (e.g., mild climate), using eQUEST as energy simulation tool. Detailed load profiles for the four commercial building types during times of peak electric and peak gas consumption were analyzed and complementary strategies to further increase overall building energy efficiencies such as energy efficiency measures (e.g., day lighting, exterior shading, improved HVAC performance) and thermally activated absorption cooling were also investigated. Results show that the high-temperature fuel cell (HTFC) performance is best matched with the hospital energy loads, resulting in a 98% DG capacity factor, 85% DG heat recovery factor, and $860,000 in energy savings (6 years payback). The introduction of thermally driven double-effect absorption cooling (AC) in the college building with HTFC reduces significantly the building electricity-to-thermal load ratio and boosts the heat recovery factor from 37% to 97%.

*Keywords:* Distributed generation; Fuel cells; Micro-turbine generators; Photovoltaic arrays; Emissions; Absorption cooling; Energy efficiency measures; Load profiles; Building energy simulation

## 1. Introduction

Distributed generation (DG) has the potential to meet a significant portion of increased power demands of the future. DG applications can reduce total energy costs and pollutant emissions, especially in combined cooling, heating and power (CCHP) applications. The largest blackout in the U.S. history, which resulted in more than 50 million people in eight states losing power in August 2003, has sparked the interest of DER as a promising solution to U.S. power grid problems. According to the strategic plan for DG developed by the California Energy Commission [1], more than 2000 MW can be currently classified as DG in California, and 20% of the increased power demand is estimated to be met by DG in 2020.

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*Abbreviations:* AC, absorption cooling; ASHRAE, American Society of Heating, Refrigeration and Air-Conditioning Engineers; BO, Boston (Massachusetts); BTU, British Thermal Units (3412.14 BTU = 1 kWh); CHP, combined heat and power; CCHP, combined cooling, heating and power; $CO_2$, carbon dioxide; COLL, college/school building; COP, coefficient of performance; DER, distributed energy resources; DG, distributed generation; DG-CCHP, DG types with CCHP capabilities; DHW, domestic hot water; DOE-2, public domain building energy simulation code; *E/T*, electrical load to thermal load ratio; EEM, energy efficiency measures; EIA, energy information agency; eQUEST, graphical interface for whole-building energy analysis tool derived from DOE-2; FC, fuel cell/s; GT, gas turbine/s; HOSP, hospital building; HTFC, high temperature fuel cell/s; HVAC, heating, ventilating and air-conditioning; ICE, internal combustion engine/s; LA, Los Angeles (California); MOB, medium office building; MTG, micro-turbine generator/s; $NO_x$, nitrogen oxides; O&M, operating and maintenance; PV, photovoltaic solar panel; SCE, southern California Edison (California electric investor-owned utility); SOB, small office building; SoCalGas, southern California gas (California gas investor-owned utility)

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0378-7788/$ – see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.enbuild.2007.04.005

One of the most critical and emerging markets for DG-CCHP systems are commercial and institutional buildings. Of the total CCHP capacity in the U.S., only slightly more than 11% occurs in the commercial sector. Although the commercial sector is about 3/4th as large as the industrial sector in terms of electricity demand, the existing application of CCHP is nine times larger in the industrial sector. The recently approved U.S. CCHP roadmap [2] targeted 8 GW of new CCHP capacity in buildings by 2010. This goal is slightly more than 10% of the estimated buildings CCHP potential in the U.S. (77 GW). Promising targets include office buildings (approximately 18 GW of technical CCHP potential), schools and universities (19 GW), hospitals (9 GW), nursing homes (8 GW) and hotels/motels (7 GW) [3]. This potential could be expanded if thermally activated technologies, such as absorption cooling/refrigeration and desiccant dehumidification, can be integrated in buildings and, therefore, increase buildings' thermal energy loads, especially in places like southern California, where the mild weather conditions make space heating requirements very limited.

In order to assess the economic and environmental benefits of the integration of DG into commercial buildings, sophisticated building energy use analysis tools are required. In a recent comprehensive literature survey [4] on software tools for whole-building energy analysis, DOE-2 (and their associated DOE-2-based user interfaces) was selected as one of the six state-of-the-art tools, and was considered the most important public-domain whole-building energy analysis tool currently in use. For the current study, the enhanced DOE-2.2-derived user-interface eQUEST program was selected and used for the analysis. This program is able to calculate the hourly energy use and energy cost of several types of commercial buildings given information about weather in the building location, construction, operation, utility rate schedule, heating, ventilating, air-conditioning (HVAC) equipment, as well as DG unit performance parameters and operation strategy. In a recent Ph.D. dissertation [5] eQUEST was used to develop a design methodology for high-rise office buildings that considers regional climate adaptability during the initial design process, which can simultaneously optimize energy efficiency and minimize negative environmental impacts.

The purpose of the present work is to study the main economic, energy-efficiency, and environmental impacts of the integration of three examples of advanced DG technologies, namely high temperature fuel cells (HTFCs), micro-turbine generators (MTGs) and photovoltaics (PVs) into four types of generic commercial buildings (small office building, medium office building, hospital and school). Base cases without DG are first presented and the buildings' electric and gas hourly profiles for days corresponding to peak electric and gas consumption are analyzed. Second, different sets of cost-effective energy efficiency measures are implemented in each type of building according to energy use intensity characteristics to reduce energy consumption and emissions. Third, several cases are presented with a variety of DG type-building type combinations that only utilize available waste heat for traditional domestic hot water (DHW) and/or space heating purposes. Fourth, the traditional HVAC system is replaced with an alternative that includes an absorption chiller, which requires a hot water loop, to increase the thermal loads of the building and improve the overall efficiency of the DG unit with higher waste heat recovery utilization. Finally, the influences of utility gas and electric tariffs and weather conditions are illustrated, comparing the DG economic viability of the same office building in two U.S. locations.

## 2. Description of selected commercial building categories

Four building templates were chosen in three representative categories (offices, health care, and education) of the commercial building sector, namely a small and a medium 2-story office building, a 10-story hospital, and a 4-story school/college building.

Brief descriptions of the main features of the selected building categories and the specifics of the selected building templates are presented below.

### 2.1. *Office buildings*

According to the commercial building energy consumption survey [6], office buildings in the U.S. have the second largest amount of buildings and floor space (18% of the total commercial floor space), and they consume the most energy of all building types, accounting for 19% of all commercial energy consumption. The U.S. average electricity demand to thermal demand ratio ($E/T$) for an office building is 2.30. However, if only domestic hot water thermal load is considered (removing the seasonal space heating load, which is not always met by centralized hot water or steam), the average $E/T$ rises to 8.72. Available DG-CCHP technologies have electric to thermal ratios in the range of 0.5–2.5. Therefore, office buildings become more attractive target applications when space-heating needs are incorporated and/or when traditional electric cooling systems are replaced by advanced absorption cooling systems that can be thermally activated by the DG waste heat. The estimated DG-CCHP technical potential (estimation of market size constrained only by technological limits, no economics considered) for all office building applications in the U.S. is about 18,000 MW [3] and the market potential (based on achievable economics, where the DG-CCHP system provides a minimum payback of 10 years compared to conventional HVAC systems) is 10,500 MW [7].

### 2.2. *Health care buildings*

In the U.S., there are about 22,000 inpatient health care buildings, 16,400 of those being hospitals and the rest psychiatric facilities and rehabilitation centers. Health care buildings (both outpatient and inpatient) account for 11% of all commercial energy consumption, using a total of 0.16 million GWh (561 trillion BTU) per year. These buildings are the fourth highest consumer of total energy of all building types. Electric to total thermal demand and electric to domestic hot water demand for health care buildings in the U.S. are 0.9 and 1.69, respectively. Moreover, electric and thermal needs are often coincident and load factors (ratio of average load to peak load) are high (80–90%). All these features make hospitals perfectly suited for CCHP technologies, even in the case where only DHW demands are met by CCHP. The estimated DG-CHP technical potential for all inpatient health care applications in the U.S. is about 8400 MW [3] and the market potential is above 7000 MW [7]. In California the technical potential reaches 300 MW [8].

### 2.3. Education buildings

Education buildings are the fifth most prevalent commercial building type in the U.S., with approximately 309,000 buildings. This category includes preschools, elementary schools, middle or junior high schools, high schools, vocational schools, and college or university classrooms. They are, on average, the largest commercial buildings, with 2332 $m^2$ (25,100 $ft^2$) per building, and they account for 13% of all commercial floor space. They consume a total of 0.19 GWh (614 trillion BTU) of energy per year. Education buildings are on average less energy intensive than office buildings, and the latter less than hospitals. The relative energy intensities for these three building types are 1, 1.5–2, and 3–4, respectively. Educational buildings present a favorable electric to total thermal ratio of 0.67 for integration of a DG-CCHP system. Even when considering the heat recovery system to produce domestic hot water only, the $E/T$ ratio (1.94) is still compatible with some DG-CCHP technologies. Again, the implementation of absorption cooling can improve the overall heat recovery utilization by making electric and thermal loads more coincident and by increasing the thermal demands. The CCHP technical potential for schools only is about 15 GW and reaches 18 GW if colleges and universities are included [3], with more than 10 GW of real market potential [7]. The CCHP technical potential for educational buildings in California is 2 GW.

## 3. Characteristics of the four buildings templates

Four examples or templates of commercial buildings were considered as base cases in this study of DG integration into the built environment. First a 4645 $m^2$ (50,000 $ft^2$) 2-story office building, with typical office building characteristics, including administrative office schedules and rather low base electric load, is called small office building (SOB). A second 2-story office building with almost twice the floor space (8361 $m^2$, 90,000 $ft^2$) and the same typical features as the first one, but with a relatively higher base electric load, is called medium office building (MOB). Third, a 23,226 $m^2$ (250,000 $ft^2$) 10-story hospital (HOSP) was chosen as a typical example of a health care building. The fourth building selected is a 23,226 $m^2$ (250,000 $ft^2$) 4-story school/college building, which is abbreviated by COLL.

In most cases default parameters provided by eQuest were used to determine the structural and operating characteristics of the selected building templates. These default parameters include building shell, structure, materials, and shades; building operations and scheduling; internal loads (based on ASHRAE standards); HVAC equipment and performance (according to California's Title 24 energy efficiency standard); and HVAC zoning in a simple core-versus-perimeter zoning scheme. For the medium office building, some electric loads during unoccupied hours were modified to increase the energy intensity of the building and have two more differentiated office buildings.

All buildings were assumed to be located in southern California and long-term weather data for that area were applied. Commercial electric and natural gas utility rates in California were automatically defined by eQUEST as a function of building type and location. Complex time-of-use electric tariffs, for which energy and demand charges vary by time of day (peak, mid-peak, off-peak, etc.), were assigned to both the two office buildings (southern California Edison {SCE} GS-2 rate), as well as to the hospital and the college (SCE, TOU-8A rate). The four buildings were assigned the same natural gas commercial rate (southern California Gas {SoCalGas} GN-10), which is based on block charges. Both electric and natural gas rates were taken as of April 2002. It is important to note that the main economic conclusions of this study might change depending on the current natural gas and electricity prices, as shown in a recent economic analysis on the operating savings provided by MTGs in southern California [9]. For instance, as of September of 2004, electric rates for the hospital building are almost 40% lower and gas rates have increased 30% approximately. This combination of factors results in no energy cost savings for the DG options considered in this study.

A few cases for the small office-building template were run with Boston (MA) weather conditions. Utility tariffs for these cases (as of March 2003) were retrieved from Boston Edison and Boston Gas Internet sites and manually introduced in the program. Boston electric rates are about 40% lower and natural gas rates about 100% higher than the corresponding southern California considered for the same small office building, both circumstances unfavorable for the economics of gas-driven DG-CCHP technologies.

Table 1 summarizes the main characteristics of the four selected commercial building templates including building code, building description, area, number of floors, HVAC system, base power demand, average power demand, peak power demand, annual $E/T$ ratio, and $E/T$ ratio if absorption cooling (AC) is replacing the traditional electric cooling. The last column is an estimated valued, assuming that 35% of the electricity is used for cooling purposes and that for every one unit of electricity five units of thermal energy are needed to produce the same cooling load (COP electric chiller = 5; COP absorption chiller = 1). Note the significant change in the $E/T$ ratio when absorption cooling is added, making the office buildings and the college more compatible with DG-CHP technologies.

Table 1
Main characteristics of selected commercial building templates

| Building code | Description | Area ($m^2$) | No floors | HVAC system | Base power demand (kW) | Average power demand (kW) | Peak power demand (kW) | Annual *E*/*T* ratio | Annual *E*/*T* ratio with AC |
|---|---|---|---|---|---|---|---|---|---|
| SOB | Small office building base case | 4,645 | 2 | Packaged single zone DX coils, with furnace | 11 | 55 | 270 | 31.7 | 0.45 |
| MOB | Medium office building base case | 8,361 | 2 | Packaged single zone DX coils, with furnace | 100 | 165 | 460 | 44.9 | 0.45 |
| HOSP | Hospital base case | 23,226 | 10 | Dual duct air handler with HW heat, chiller and hot water coils | 900 | 1105 | 1300 | 1.1 | 0.29 |
| COLL | College/school base case | 23,226 | 4 | Packaged single zone DX coils, with furnace | 70 | 370 | 1450 | 11.5 | 0.44 |

## 4. Energy efficiency measures (EEM)

The first consideration before attempting a DG building integration is to maximize efficiency in the building's energy demands. Designers should minimize the electricity and thermal load by utilizing energy-efficiency design strategies such as building envelope improvements, day lighting techniques, and natural ventilation applications. Furthermore, installing energy-efficient lighting and cooling equipment throughout the building minimizes energy loads [10].

Prior to any analysis with distributed generation systems implemented in the building, we established different sets of energy efficient measures (EEM) that are most suited for the specific type of building in consideration [11]. The set of energy efficient strategies introduced in each building category are presented in Table 2. Simulation results of EEM cases consistently illustrate a 5–20% annual reduction in electricity consumption, $CO_2$ (greenhouse gas) and $NO_x$ (criteria pollutant) emissions and utility costs compared to the base cases (Table 3). The rest of the energy simulation results with DG systems and with absorption chillers described below will be compared with the EEM base cases.

## 5. Characteristics of selected DG types

The traditional and most widely adopted DG technologies in the current electric generation market are internal combustion engines (ICE) and gas turbines (GT). However, in this work we consider three advanced DG types that are relatively new in the market, presenting potential environmental and energy-efficiency benefits over the traditional systems. These advanced types include fuel cells, micro-turbines (MTGs), and photovoltaic (PV) solar panels.

For this study generic units were considered for each DG type having specific power capacities, electric and overall efficiencies, performance parameters, and economic data, as shown in Table 4. The fuel cell is a high temperature fuel cell (HTFC) with a peak power generating capacity of 250 kW, the MTG has a peak power generating capacity of 60 kW and the PV unit (an array of high-efficient multi-crystalline silicon) has a peak power generating capacity of 60 kW. Part load performance curves for power output and heat recovery were input into the electric generator modules of eQUEST for the MTG and for the HTFC based on open literature data for the former [12] and based on the authors' understanding of these technologies for the latter. For the 60 kW PV unit, the generic built-in PV multi-crystallinemodule available in eQUEST was applied. The units selected do not represent any particular manufacturer's products. Thus, results presented in this report can be extended to any unit with similar characteristics to the generic ones considered in this analysis.

Table 2
Set of energy efficiency measures (EEM) implemented for each building type

| Type of building | Energy efficiency measures |
|---|---|
| Office buildings | Windows exterior shading (overhangs)<br>Day lighting controls<br>15% increase in HVAC cooling efficiency |
| Hospital | 4 °F lower condenser water temperatures<br>15% increase in HVAC cooling efficiency |
| College | Windows exterior shading (overhangs)<br>Day lighting controls<br>15% increase in HVAC cooling efficiency |

## 6. Characteristics of absorption cooling

Absorption cooling was included in the study as an alternative to the traditional HVAC system with electric compression cooling. Absorption chillers can be used to reshape the thermal and electric profile of a facility by shifting cooling from an electric load to a thermal load. The shift can be very cost-effective for facilities with time-of-day electrical rates or high cooling season rates. For DG-CCHP applications, since cooling predominates during the warmer season and space heating is required during cooler seasons, absorption chillers provide an effective year-round thermal load factor.

Hot water, indirect fired double-effect absorption chillers with enough cooling capacity to serve peak cooling demands were used in the simulation. A COP of 1.1 was assumed in all cases with absorption cooling and the eQUEST default part load performances curves for double-effect absorption chillers was used. As capital and operating and maintenance (O&M) costs of an absorption chiller system varies with the cooling capacity of the unit, two different sets of costs were considered in the simulations: \$950/t (capital cost, including cooling tower,

Table 3
List of simulated base cases and DG building integration cases

| Case code | Description | Primary energy consumption (GWh/year) | $CO_2$ emission t/year | $NO_x$ emission kg/year | DG utilization factor (%) | Heat recovery factor (s) | Electric bill (k$/year) | Natural gas bill (k$/year) | O&M costs for DG and AC (k$/year) | Pay back period (year) |
|---|---|---|---|---|---|---|---|---|---|---|
| SOB | 2-Story office building, 53,520 ft$^2$ | 1.64 | 300 | 763 | – | – | 88.5 | 0.8 | – | – |
| MOB | 2-Story office building, 90,000 ft$^2$ | 4.87 | 889 | 2,266 | – | – | 223 | 1.5 | – | – |
| HOSP | 10-Story hospital, | 46.61 | 8,507 | 18,367 | – | – | 1242 | 227.0 | – | – |
| COLL | 4-Story school/college, | 11.19 | 2,041 | 5,131 | – | – | 622 | 8.7 | – | – |
| SOB EEM | SOB + EEM | 1.40 | 255 | 648 | – | – | 74 | 0.8 | – | – |
| MOB EEM | MOB + EEM | 4.49 | 818 | 2,085 | – | – | 202 | 1.5 | – | – |
| HOSP EEM | HOSP + EEM | 45.57 | 8,316 | 17,878 | – | – | 1200 | 227.0 | – | – |
| COLL EEM | COLL + EEM | 9.32 | 1,700 | 4,257 | – | – | 500 | 8.7 | – | – |
| MOB HTFC | MOB EEM + 1HTFC | 3.13 | 896 | 582 | 100 | 3 | 32.2 | 48.2 | 8.4 | 12.0 |
| MOB HTFC AC | MOB EEM + 1HTFC + AC | 3.55 | 977.4 | 582 | 100 | 47 | 5.3 | 60.7 | 16.9 | 13.2 |
| HOSP 4HTFC | HOSP EEM + 4HTFC | 26.0 | 7,231 | 5,098 | 98 | 85 | 134.8 | 368.7 | 59.5 | 6.4 |
| COLL HTFC | COLL EEM + HTFC | 7.8 | 1,700 | 3,002 | 47 | 37 | 343.8 | 38.1 | 6.6 | 11.5 |
| COLL HTFC AC | COLL EEM + HTFC + AC | 9.9 | 2,382 | 3,685 | 47 | 97 | 257.1 | 106.3 | 25.2 | 7.8 |
| SOB MTG | SOB_EEM + 1MTG | 1.57 | 262 | 445 | 32 | 4 | 47.0 | 14.7 | 1.6 | 14.1 |
| SOB MTG AC | SOB_EEM + 1MTG + AC | 1.77 | 300 | 471 | 32 | 90 | 38.1 | 20.4 | 6.7 | 27.6 |
| MOB 2MTG | MOB_EEM + 2MTG | 5.65 | 877 | 910 | 100 | 2 | 79.3 | 73.5 | 9.4 | 7.0 |
| MOB 2MTG AC | MOB_EEM + 2MTG + AC | 5.89 | 920 | 90 | 100 | 30 | 56.6 | 81.6 | 17.6 | 10.5 |
| HOSP 15MTG | HOSP EEM + 15MTG | 44.35 | 6,953 | 5,728 | 98 | 38 | 228.5 | 613.0 | 77.6 | 4.3 |
| HOSP 15 MTG AC | HOSP EEM + 15 MTG + AC | 39.94 | 6,142 | 3,710 | 98 | 79 | 32.2 | 614.5 | 91.0 | 3,7 |
| COLL MTG | COLL EEM + MTG | 9.56 | 1,669 | 3,493 | 100 | 24 | 432.6 | 44.7 | 5.5 | 5.7 |
| SOB PV | SOB_EEM + 1PV | 1.09 | 199 | 505 | 49 | – | 59.8 | 0.8 | – | 25.0 |
| SOB BO | SOB_EEM in Boston (MA) | 1.45 | 265 | 636 | – | – | 41.85 | 8.87 | – | – |
| SOB MTG BO | SOB_EEM + 1 MTG in Boston (MA) | 1.63 | 273 | 422 | 32 | 5 | 26.9 | 36.2 | 1.7 | – |
| SOB MTG AC BO | SOB_EEM + 1 MTG + AC in Boston (MA) | 1.81 | 306 | 458 | 32 | 90 | 21.5 | 20.4 | 6.8 | – |

Table 4
Main characteristics of selected DG generic units

| DG code | Description | Peak power (kW) | Electric efficiency (LHV) (%) | Overall efficiency (%) | *E*/*T* ratio | Turndown ratio[a] | Operating mode | O&M costs ($/kWh) | Total cost (capital + installation) ($/kW) |
|---|---|---|---|---|---|---|---|---|---|
| HTFC | Generic high temperature fuel cell | 250 | 47 | 85 | 1.2 | 0.3 | Tracking electrical load | 0.007 | 5000[b] |
| MTG | Generic micro-turbine | 60 | 27 | 85 | 0.5 | 0.2 | Tracking electrical load | 0.01 | 2400 |
| PV | Generic photovoltaic panel | 60 | 11.8 | – | – | 0.02 | Tracking electrical load | – | 6000[b] |

[a] Ratio of the minimum power output to the maximum power output.

[b] Including California rebates.

pump, and piping) and $38/t (O&M) for the two office buildings; and $700/t and $25/t for the hospital and the college building applications, which require larger cooling capacities [13].

## 7. Building simulation assumptions

Assumptions made in developing the building simulations, many of which were described in the previous section, are listed below:

- All base case building simulations have default eQUEST values by building type for building shell, structure, materials and shades, building operation and scheduling, internal loads, and HVAC equipment and performance.
- In all building type cases the number of integrated DG units implemented is as close as possible to the base load electric demand (e.g. only a 60 kW MTG is considered in the small office building because its base electric load is only 11 kW).
- All DG systems are always following electrical load. No electricity is sold back to the grid.
- Waste heat from the DG units is only used in one water loop. When a building has more than one hot water loop (e.g., domestic hot water and space heating), waste heat is used in the one with larger annual thermal demands.
- Waste heat storage is not considered. If the waste heat from the DG systems cannot be used in the building in the moment it is recovered, it is lost.
- All the cases with absorption chillers assume double-effect absorption chillers.
- No stand-by charges for DG systems are included in utility rates.

## 8. Building simulation parameters

eQUEST can produce large amounts of data for one building energy simulation. However, in the current study, only a few parameters that directly address the main environmental and economic impacts of the DG integration into the built-environment are reported. These building impacts include electricity and gas consumption, primary energy consumption, $CO_2$ and $NO_x$ emissions resulting from the consumption of that energy, DG unit utilization factor, capacity factor and heat recovery factor, electric and natural gas utility costs, O&M costs and cost savings, all on an annual basis. Simple payback periods are also included when comparing a base case building with a DG integrated building. Some of the above parameters are direct outputs from the simulations, and others need to be post-processed based upon eQUEST output results. Parameters that require further explanation are described below.

- *Primary energy consumption* (*PEC*) is the sum of the natural gas energy consumption and the primary energy required in the power plant to produce the electricity consumed in the building. The U.S. average of 30% electric efficiency for large power plant power production was applied [8].
- *$CO_2$ and $NO_x$ emissions* are determined from the electricity supplied by the utility grid, the electricity supplied by the DG unit/s, and the natural gas consumed by the boiler to meet the building thermal loads. The emissions factors to convert electricity delivered or gas consumed to generated emissions are shown in Table 5 [14].
- The *DG utilization factor* is defined as the number of hours that the DG unit/s have been operating in a year both at full load and part load divided by the total number of hours in that year. Note that with this definition a 100% utilization means the unit was operating all year, but this factor does not indicate the load of the unit at each hour of that year.
- The *DG capacity factor* of the unit (total electricity generated divided by the maximum electricity the unit could have generated at full load) will always be lower than or equal to the above-defined DG utilization factor.
- The *DG heat recovery factor* is defined as the waste heat that was actually used in the building for thermal loads (including absorption cooling) over the total waste heat available from the DG. The higher the heat recovery factor, the higher the overall efficiency of the building-integrated DG and more profitable the DG investment.

Table 5
Efficiency, $CO_2$ and $NO_x$ emissions factors for the average U.S. grid, a typical boiler, a HTFC, a MTG, and a PV unit

| | $NO_x$ (kg/kWh) | $CO_2$ (kg/kWh) | Efficiency (%) |
|---|---|---|---|
| U.S. grid | $1.56 \times 10^{-3}$ | 0.610 | 30 |
| Boiler[a] | $2.28 \times 10^{-4}$ | 0.183 | 85 |
| MTG | $3.18 \times 10^{-4}$ | 0.682 | 27 |
| HTFC | $3.18 \times 10^{-5}$ | 0.386 | 47 |
| PV | 0 | 0 | 12 |

[a] Units in kg per kWh of natural gas in the boiler.

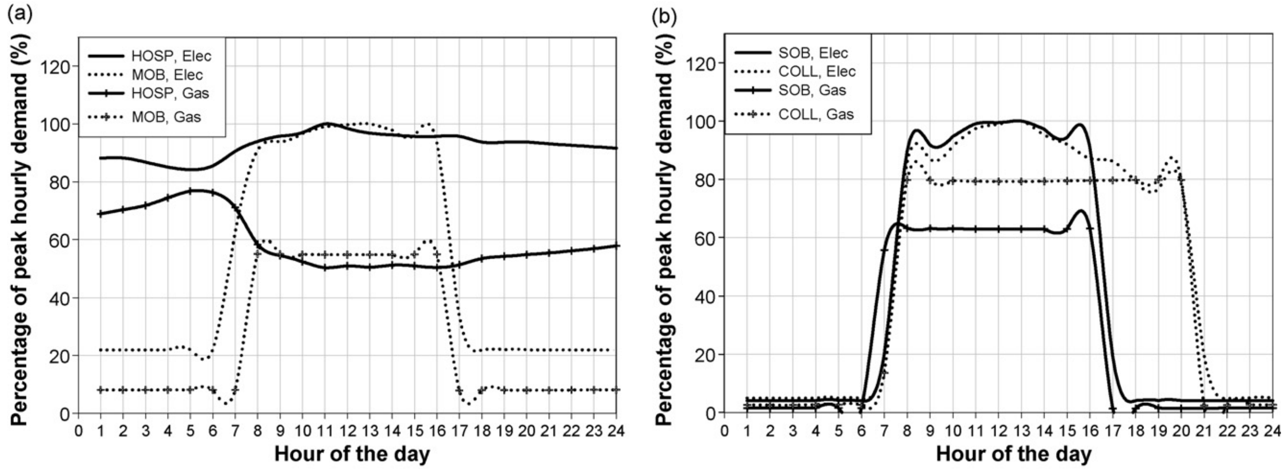

Fig. 1. Electric and natural gas hourly profiles for the peak electric day. (a) Hospital and medium office building load profiles; (b) small office building and college/school load profiles.

- *Cost savings* is the difference of the energy costs of the base case building with EEM included, and the energy costs of the same building with additional integration of DG and absorption cooling (if any) plus the associated O&M costs of both devices.
- The simple *payback period* is the number of years that it will take to recover the capital cost of the DG units and the absorption chiller unit (if any), assuming that the calculated first year savings are achieved every year, without taking into account inflation or time-value of money. It is defined as the ratio of the total cost (capital and installation costs) of the DG units and the absorption unit, and the first year energy cost savings.

## 9. Results and discussion

### 9.1. Load profile engineering of base cases

In this section the hourly electrical and gas load profiles in the peak electric day and the peak gas day for the four selected buildings in Los Angeles are presented and discussed. These load profiles form the basis for understanding the annual building results that are shown below. The load profiles were produced running the DOE-2-derived building model for each base case building. In order to plot all profiles in the same scale, hourly profiles are shown as percentages of the peak hourly load, which occurs in August for electricity and in January for gas. Fig. 1 shows the electric and natural gas hourly loads in the peak electric day (August) for the four commercial building templates considered and Fig. 2 presents the same loads for the peak gas day (January).

Among the buildings studied, the hospital has the flattest electrical and gas load shapes, both for the summer peak electric day and the winter peak gas day. Furthermore, the hospital requires a considerable amount of thermal loads year-round, with *E*/*T* ratios of about 1.2 and 0.6 for the peak electric day and the peak gas day, respectively (*E*/*T* ratios not reproducible from the plots because actual energy units are not displayed). These ratios are very well matched with the DG/CHP types in the study (*E*/*T* HTFC: 1.2, *E*/*T* MTG: 0.5). Thus,

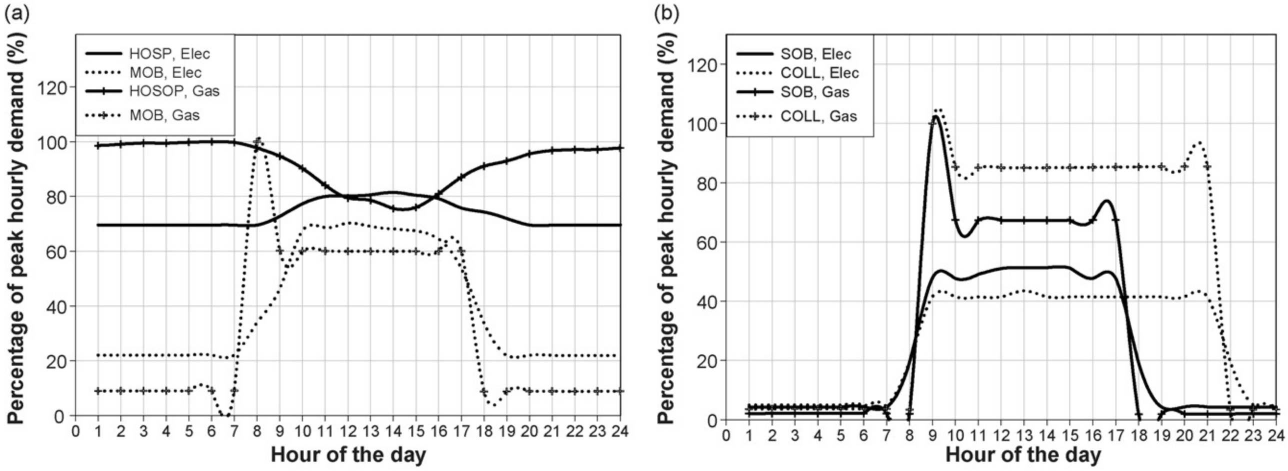

Fig. 2. Electric and natural gas hourly profiles for the peak natural gas day. (a) Hospital and medium office building load profiles; (b) small office building and college/school load profiles.

the hospital template is a strong candidate for the integration of DG with CCHP, even without the consideration of absorption cooling to increase thermal loads.

The two office buildings have very similar electric and thermal load profiles both for summer and winter peak days, but the small office building presents a much lower base electric load (4% of peak) than the medium office (22%), as expected due to the previously mentioned increased non-occupancy loads for the latter. The electric load in the peak electric day reaches a practically flat maximum during typical working hours (7–8 a.m. to 4–5 p.m.), with a slightly reduced interval (9–10 a.m. to 4–5 p.m.) in the gas peak day due mainly to the decrease in cooling loads. Although the thermal gas loads of the office buildings are very coincident to the electrical load, which is ideal for CCHP, the thermal load is 2 orders of magnitude lower than the electric energy demand. Note that in the gas peak day there is a sharp peak for gas load around 8–9 in the morning. This is the only space-heating load required for the office building in the mild winter weather of southern California, and the remaining gas loads are for DHW. Thus, only a small fraction of the waste heat rejected by the DG-CCHP unit tracking electric load could be used in traditional thermal loads, and the potential application of traditional CHP is marginal due to the poor economics. However, the use of advanced thermally activated technologies such as absorption cooling to increase thermal loads will make these buildings much better candidates for a cost-effective DG-CCHP implementation.

The college/school building template shows the most remarkable decrease of about 60% in the electric load between the peak electric day and the peak gas day due to the considerable amount of cooling required for this building in summer. In comparison with the office buildings, it also presents a longer period with high electric demand due to the extended occupancy schedule of the college. Thermal loads are fairly constant throughout the year and are very well matched with the electric load profile. The electric to thermal ratios both in summer (22) and winter peaks (16) are approximately three times lower than for the office buildings, but they are still too high to match the DG-CCHP power and heat co-production ratios well, so most of the available waste heat would be lost if no additional thermal demands are required or some kind of thermal storage strategy is implemented.

### 9.2. Integration of DG types

Building integration results for three generic DG units representing three advanced DG technologies, namely high temperature fuel cells, micro-turbine generators and photovoltaic solar panels, are presented and discussed below. Table 3 shows the list of the selected building cases for this report (including base cases, base cases with EEM, and multiple cases with combinations of commercial building types with DG types, with and without absorption cooling) and their main performance outputs.

The cost savings of the integration of one or more HTFCs into a hospital, a college, and a medium office building in southern California in comparison with the corresponding base cases with EEM included are presented in Fig. 3. For the hospital, four 250 kW HTFCs are needed in order to cover the base electric load whereas for the college and the medium office buildings just one HTFC significantly exceeds the base loads. The annual electric and natural gas utility bills for the hospital, the college, and the medium office buildings are reduced by 61%, 24%, and 56%, respectively. That translates to hospital savings of more than $860,000 in annual energy costs (O&M costs for the four HTFCs included). Savings for the college and the medium office buildings reach $120,000 and $114,000, respectively.

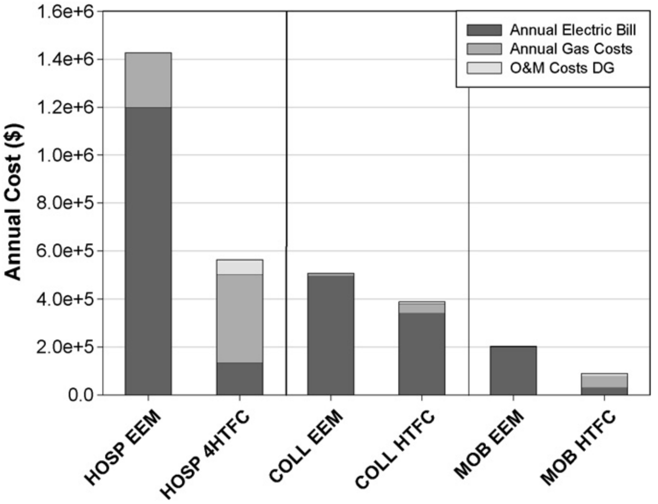

Fig. 3. Annual electric, natural gas, and DG operating and maintenance costs for a hospital, a college, and a medium office building with and without integrated high temperature fuel cells (HTFC).

The economics of the integration of MTGs instead of HTFCs is also studied for the four building templates considered, as shown in Fig. 4. According to their base electric load, 1 60 kW MTG is adopted in the small office

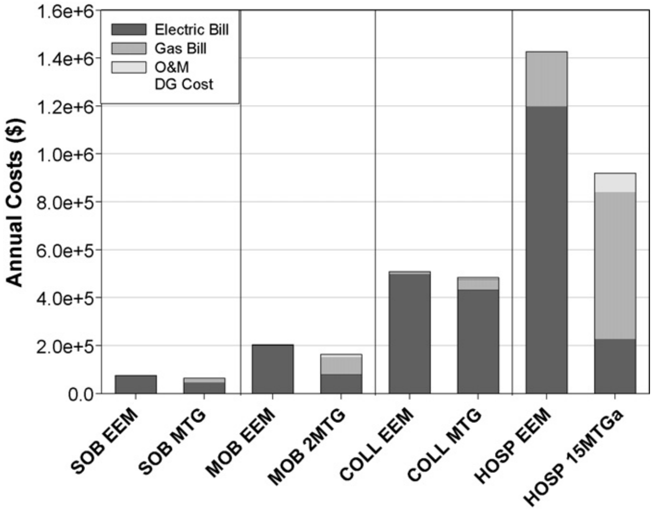

Fig. 4. Annual electric, natural gas, and DG operating and maintenance costs for a hospital, a college, a medium office building, and a small office building with and without integrated micro-turbine generators (MTG).

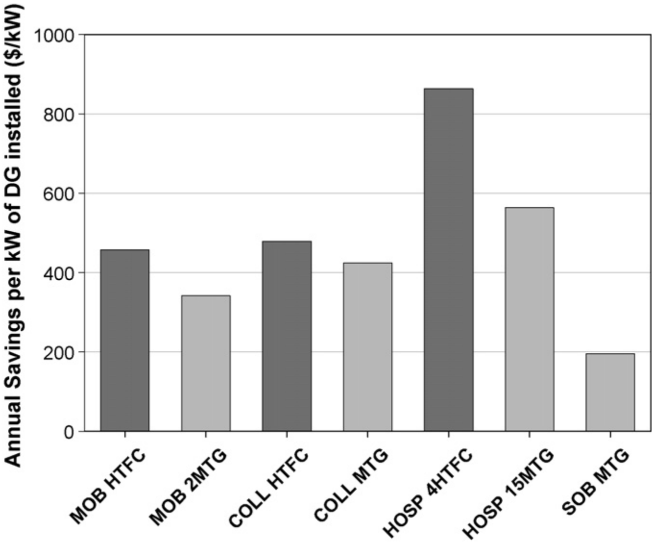

Fig. 5. Annual savings per kW of DG power installed for various cases of DG-CHP integrated in commercial buildings.

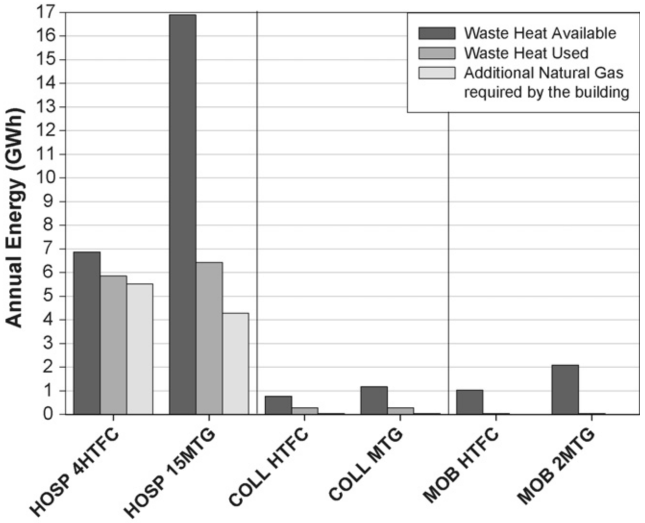

Fig. 6. Waste heat available, waste heat used and additional natural gas required for various cases of DG-CHP integrated in commercial buildings.

building and the college, 2 MTGs in the medium office building and 15 MTGs in the hospital. The annual savings in these cases are about: $12,000, $25,000, $41,000 and $507,000, respectively. Note that cost reductions are not just proportional to the number of DG units, but are also influenced by other parameters such as the DG annual operating schedule, the electricity and natural gas rate structures, and the amount of waste heat recovered. Comparing the annual savings of all the cases with MTGs and with HTFCs on the same power output basis, as shown in Fig. 5, the hospital building combined with four HTFC yields the highest savings, with about $300/year/kW additional savings compared to the second best case, the hospital with 15 60 kW MTGs. As expected due to their higher electrical efficiency, HTFC integration provides, in general, more savings per kW than the corresponding MTG cases. However, as shown in Table 3, payback periods for MTG installations are usually shorter (4.3–7 years) than for HTFCs (6–12 years) due to the much lower capital costs of MTGs.

Although the integration of a 60 kW multi crystalline PV array into a small office building (Table 3) produces annual reductions in energy costs (19%) and $CO_2$ and $NO_x$ emissions (22%), PV's high capital costs result in a payback period of about 25 years.

The implementation of both HTFCs and MTGs in the hospital building is, in both cases, more cost-effective than in the other buildings for two main reasons. First, the capacity factor of the DG units in the hospital is close to 100% because of the previously described nearly flat electricity loads throughout the year and because the number of DG units meets very closely the base electric load of the hospital template studied. Second, as the thermal loads of the hospital are much higher than any of the other building examples, proportionally much less waste heat rejected by the DG units is lost (Fig. 6), improving the overall efficiency of the system. The DG heat recovery factor is about 85% for the hospital with four HTFCs and goes down to 37% with the same building and 15 MTGs. The model uses the waste heat only for the space heating water loop in the hospital. Thus, the considerable amount of natural gas needed in the two hospital cases is not due to the eventual temporal mismatch between waste heat availability and space heating load, but is rather due to the second domestic hot water loop that is driven by natural gas.

The college/school building utilizes 37% of the HTFC waste heat and 24% of the MTG waste heat for domestic hot water purposes, almost completely replacing the base case natural gas demand (Fig. 6). The two DG-CCHP integrated cases with the medium office building present only 3% and 2% annual waste heat utilization factor for the HTFC and the MTG cases, respectively, which explains why these DG integrated cases show the least annual economic savings per unit of installed DG power.

Fig. 7 shows the DG utilization factor, the capacity factor, and the heat recovery factor for four DG cases in which a double-effect indirect absorption chiller was included in the HVAC system of the building and compares them with the same DG cases with the default HVAC system by building type, which in all cases implies electricity-driven cooling. As expected, the increase in utilization of thermal energy due to the introduction of thermally activated cooling provides a general boost to the DG heat recovery factor. For the medium office building, waste heat utilization increases from 2% to 30% for the 2 MTG case and from 3% to 47% for the 1 HTFC case. Still, a majority of the waste heat available is lost because the relatively high base load of this building (100 kW) requires both the MTG and HTFC to operate during night hours, when no cooling or heating loads are required. The college building with one integrated HTFC can significantly increase the heat recovery factor from 37% to 97% when cooling loads are thermally driven instead of electricity-driven. In this case, as the base electric load is lower than the minimum-operating ratio of the HTFC, the HTFC does not operate at night and, therefore, no rejected heat is wasted. Thus, available waste heat

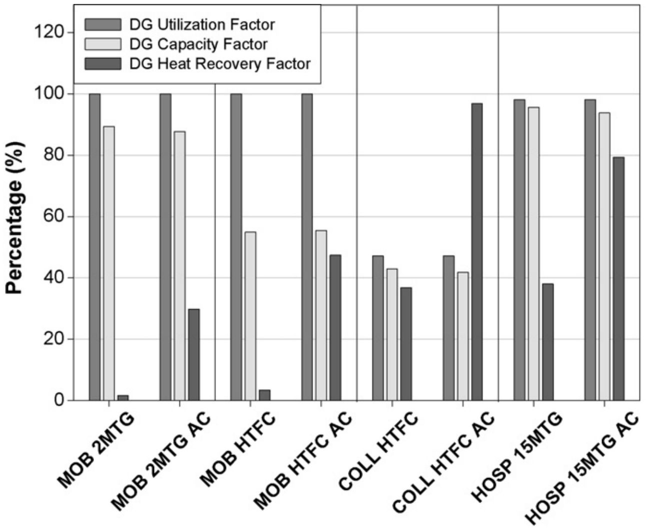

Fig. 7. DG utilization factors, capacity factors, and heat recovery factors for various cases of DG-CHP commercial buildings with and without integrated absorption cooling (AC).

and cooling load profiles are almost coincident and most of the waste heat is utilized. Regarding the hospital with 15 MTGs, it was previously pointed out that summer *E*/*T* ratios (1.2) are not very well matched with MTG *E*/*T* ratio (about 0.5). Furthermore, waste heat is only used in the hot water space-heating loop, which means that the summer mismatch between space heating thermal loads of the hospital and the waste heat produced by the 15 MTGs is still more pronounced. This explains the relatively low yearly averaged heat recovery factor of 38%. This figure is doubled (79.3% of heat recovery utilization) when a double-effect absorption chiller replaces the typical electric compression chiller. Still, some temporal mismatches in the early and late hours of summer days, when cooling demand is low and yet waste heat availability is high, result in more than 20% of the available heat being wasted.

The increase in the overall DG efficiency of all these commercial buildings when absorption cooling is implemented results in improved annual energy costs, even when the O&M costs for the absorption chiller are included. However, the inclusion of the rather expensive capital cost of the absorption chiller and the associated equipment (cooling tower, pump, piping, etc.) normally implies longer payback periods, except for the hospital case, in which the considerable additional savings of shaving the electric cooling loads and doubling the waste heat utilization balances with the absorption chiller investment cost (3.9 years without absorption chiller versus 3.5 years with absorption chiller).

### 9.3. *Effect of building location*

The same exact building can present completely different DG building integration outputs in two different locations in the U.S., due both to weather conditions and different natural gas and electricity tariffs. To assess the effects of this change of building location in a particular example, the same small office building cases SOB EEM, SOB MTG, and SOB MTG AC were run with exactly the same input parameters except weather conditions and electric and natural gas tariffs. The weather conditions and utility tariffs are those corresponding to the Boston area (MA). The main output results for those simulations are presented in the last three rows of Table 3.

Fig. 8 compares the monthly electric and natural gas consumption and utility costs for the same office building in Los Angeles and in Boston. Electric monthly loads in Los Angeles are slightly higher (3–20%) than the corresponding ones in Boston, due to the small additional cooling that the building needs in Los Angeles, especially in spring and fall months. Due to the harsher weather conditions in Boston, thermal loads for space heating in wintertime are considerably higher in Boston than in Los Angeles, whereas the domestic hot water demands are very similar. Thus, gas loads in winter months are about 10–20 times higher in Boston. From May to

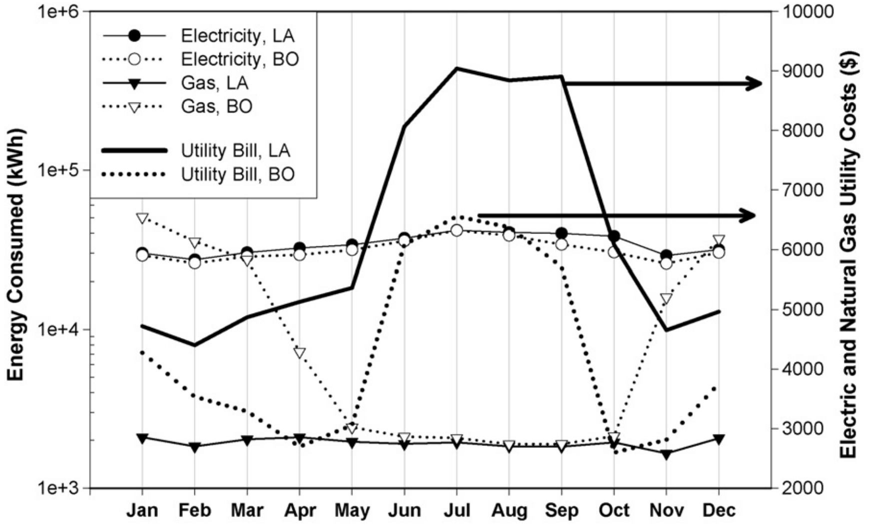

Fig. 8. Comparison of monthly electricity and natural gas consumption and monthly utility bills for the same small office building located in Los Angeles area (CA) and Boston area (MA).

October space heating is not needed any more, and gas loads in both locations show nearly the same values. Despite the larger amount of annual primary energy used for the SOB in Boston, the annual electric and natural gas bill in Boston is 32% less than in Los Angeles. The reason for this is that electricity grid prices in Boston are about 40% lower than in Los Angeles. The almost 100% higher natural gas rates in Boston make less of a difference than the above-mentioned difference in electricity prices because natural gas consumption in the small office building is relatively low. This example also illustrates how the combination of relatively cheap electricity and expensive natural gas can make the economics of DG and absorption cooling integration not viable, although environmental benefits of this integration in terms of reductions of primary energy consumption and $NO_x$ emissions do still apply.

## 10. Conclusions

A set of whole-building energy simulation cases were run and analyzed using a DOE-2 derived tool to study the impacts of advanced building energy-efficiency strategies on 4 representative examples of commercial buildings. The main findings of this analysis are presented as follows:

- The application of energy efficiency measures well-suited for each building type, such as day lighting controls, windows shading, and more efficient HVAC systems, should be considered before attempting a DG building integration. Those measures can contribute to important energy savings with minor investment. The commercial buildings studied with these measures resulted in energy savings in the range 5–20%.
- Hourly load profiles both for electric and thermal loads are key to better understanding the energy consumption characteristics of commercial buildings and predicting how well distributed generation systems and absorption chillers can be integrated. The hospital case represents the most compatible match with distributed generation with heat recovery integration due to a coincident and flat electric and thermal loads, and to a relatively low electric to thermal ratio (1.1), within the range of electricity to thermal energy ratios of DG types (0.5–2.5). The college/school and the office building cases do not show such a favorable match with micro-turbines and high temperature fuel cells in terms of load profiles and electricity to thermal load ratios, but they can improve the efficiency of distributed generation integration if thermally activated absorption chilling is implemented for cooling loads.
- The integration of high temperature fuel cells into a hospital, a college, and a medium office building located in southern California to meet base electric loads result in annual savings of $860,000, $120,000 and $114,000, respectively, and the associated payback periods are 6.4, 11.5, and 12 years, respectively. The corresponding values for the integration of micro-turbines with the same buildings are annual savings of $507,000, $25,000, and $41,000, and payback periods of 4.3, 5.7, and 7 years.
- Integration of a 60 kW photovoltaic array into a small office building can produce significant annual reductions in energy costs (19%) and $CO_2$ and $NO_x$ emissions (22%), but the high capital costs of photovoltaic panels result in a pay-back period of about 25 years.
- High temperature fuel cells performance is best matched with the hospital case energy loads, resulting in a 97% capacity factor and a heat recovery factor of 85%. High temperature fuel cell capacity and heat recovery factors for the college and the medium office cases are significantly lower, and, therefore, lower savings per unit of distributed generation power are achieved in these cases. Micro-turbines integration with the hospital shows the same capacity factor of 97%, but a much worse heat recovery factor (38%), due to the lower electric efficiency of the micro-turbine in comparison to the high temperature fuel cell.
- Replacement of traditional electric cooling by absorption cooling provides in most of the cases studied a significant increase in the overall efficiency of the combined heat and power system and in the annual economic savings. For example, heat recovery factor is increased from 37% to 97% when an absorption chiller is introduced for the college building with high temperature fuel cell case.
- The small office building in Boston has similar electric loads and much higher gas loads than the same building in Los Angeles. However, Boston electric rates are 40% less and Boston natural gas rates are 100% more than those in Los Angeles, which results in a 32% smaller annual utility bill for Boston small office building and non-cost-effective distributed generation integration cases.

## Acknowledgements

Marc Medrano thanks the Balsells-Generalitat of Catalonia Fellowship initiative and the UCI Advanced Power and Energy Program (APEP) for support of a rewarding three-year postdoctoral research appointment at the National Fuel Cell Research Center (NFCRC).

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