Fuel Cells Economic Analysis Report

Submitted to:

California Air Resources Board
1001 I Street
Sacramento, CA 95812
Contract # 02-329

Submitted by:

National Fuel Cell Research Center
University of California, Irvine
Irvine, California 92679-3550
(949) 824-1999

Investigators:

Professor Scott Samuelsen
Dr. Marc Medrano Martorell
Jeff Wojciechowski

April 23, 2004

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AC	Absorption Cooling
ARB	Air Resources Board
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
Btu	British Thermal Units (3412.14 Btu = 1 kWh)
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
COLL	College/school building
COP	Coefficient of Performance
CSFCC	California Stationary Fuel Cell Collaborative
DER	Distributed Energy Resources
DG	Distributed Generation
DG-CHP	DG types with CHP capabilities
DHW	Domestic Hot Water
DoD	Department of Defense
DOE-2	Public domain building energy simulation code
E/T	Electrical load to thermal load
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 Ángeles (California)
LAWDP	Los Angeles Department of Water and Power
MCFC	Molten Carbonate Fuel Cell
MOB	Medium Office Building
MTG	Micro turbine generator/s
NFCRC	National Fuel Cell Research Center
NO_x	Nitrogen Oxides
O&M	Operating & Maintenance
PAFC	Phosphoric acid fuel cell
PEMFC	Proton Exchange Membrane Fuel Cell
PV	Photovoltaic solar panel
SCE	Southern California Edison (California electric investor-owned utility)
SOB	Small Office Building
SOFC	Solid Oxide Fuel Cell
SoCalGas	Southern California Gas (California gas investor-owned utility)
URL	Uniform Resource Locator

1. INTRODUCTION

The National Fuel Cell Research Center (NFCRC) under the Regents of the University of California was retained by the Air Resources Board (ARB) to conduct research and outreach work in support of the California Stationary Fuel Cell Collaborative (CaSFCC) goals. The number of the contract awarded by the ARB is #02-329. This final report describes the details of this effort and the deliverables achieved at the end of the contract.

2. TASK 1: REVIEW OF FUEL CELL ECONOMICS

The purpose of this task was to conduct a review of fuel cell (FC) economics as well as other advanced distributed generation (DG) systems such as micro turbine generators (MTG) and photovoltaic arrays (PV). Two subtasks were identified and developed for this element. The first subtask was to analyze and summarize the main highlights of the recent fuel cell manufacturers' survey on projected costs for installation of stationary fuel cell power plants in the State of California carried out by the CaSFCC [1]. The second subtask was to compile information on the economic and performance characteristics of fuel cell products that are currently commercial or about to be commercial and implement these data on an Internet-accessible database. The same information was also collected from several manufacturers and implemented in the database for two other competing advanced distributed generation technologies, namely micro turbine generators and solar photovoltaic arrays. The following sections describe in more details the two subtasks.

1.1 Highlights of the 2003 CaSFCC Fuel Cell Manufacturers Survey

This survey [1] presents the main findings from a series of interviews that took place in August, 2003 with major fuel cell manufacturers of phosphoric acid, molten carbonate, proton exchange membrane, and solid oxide stationary fuel cells. These interviews aimed to determine the current and projected manufacturing capabilities, sales volumes, and costs for installation of stationary fuel cell power plants in the state of California over the past year and to project these data over the next three years. The survey also identified actions that the State could take in order to create a more receptive environment for fuel cell installations.

The survey concluded that while the expectations for the commercial fuel cell market have been tempered since last year's survey, the companies surveyed still expect significant growth over the next few years. The projections show the industry on a growth trend with no expectations for the growth to plateau. Recent changes in the economics of electricity generation and the incentives and regulations surrounding fuel cell distribution as well as the slower growth of the U.S. economy have made companies more cautious about implementing aggressive growth plans.

Figure 1 shows the aggregated projected manufacturing capacity and sales for the fuel cell manufacturers interviewed. Current production capacity begins at a little over 100 MW and rises until 2006 when new production facilities will come on line doubling manufacturing capacity.

The projected sales go from a starting point of 9 MW in 2003 increasing to over 60 MW in 2006—almost doubling MW sales each year for the next three years. The steady projected increase reflects the growing interest and market introduction of fuel cells while recognizing the logistical, technological and economic barriers that have a dampening or delaying effect on sales.

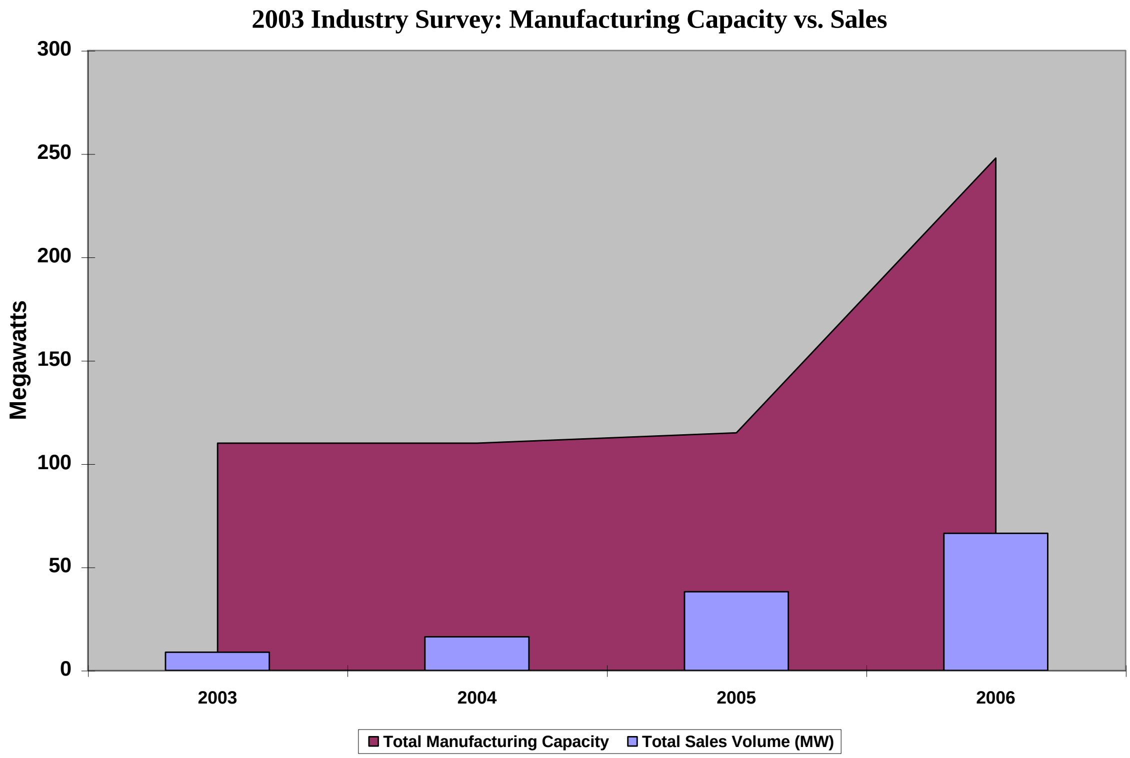


Figure 1: Projected fuel cell manufacturing capacity versus sales

Figure 2 shows the evolution of weighted average capital costs projected by the fuel cell manufacturers until 2006. The 2003 survey indicates weighted average cost starting at over $4,700/kW and decreasing to slightly over $3,100/kW (Figure 3). The range started at $4,000/kW up to $17,500/kW in the 2003 and decreases to $2,100/kW up to $12,500/kW in 2006. In 2002's survey, the weighted average started at $4,722/kW and dropped to $1,938/kW. The 2003 survey starts higher—at $4,737/kW but only drops to $3,125/kW. The flattening of the slope reflects the lower projected sales volumes that negatively impact the possibility of capitalizing on economies of scale. The flattened line also reflects the technological constraints that keeps costs higher than originally projected.

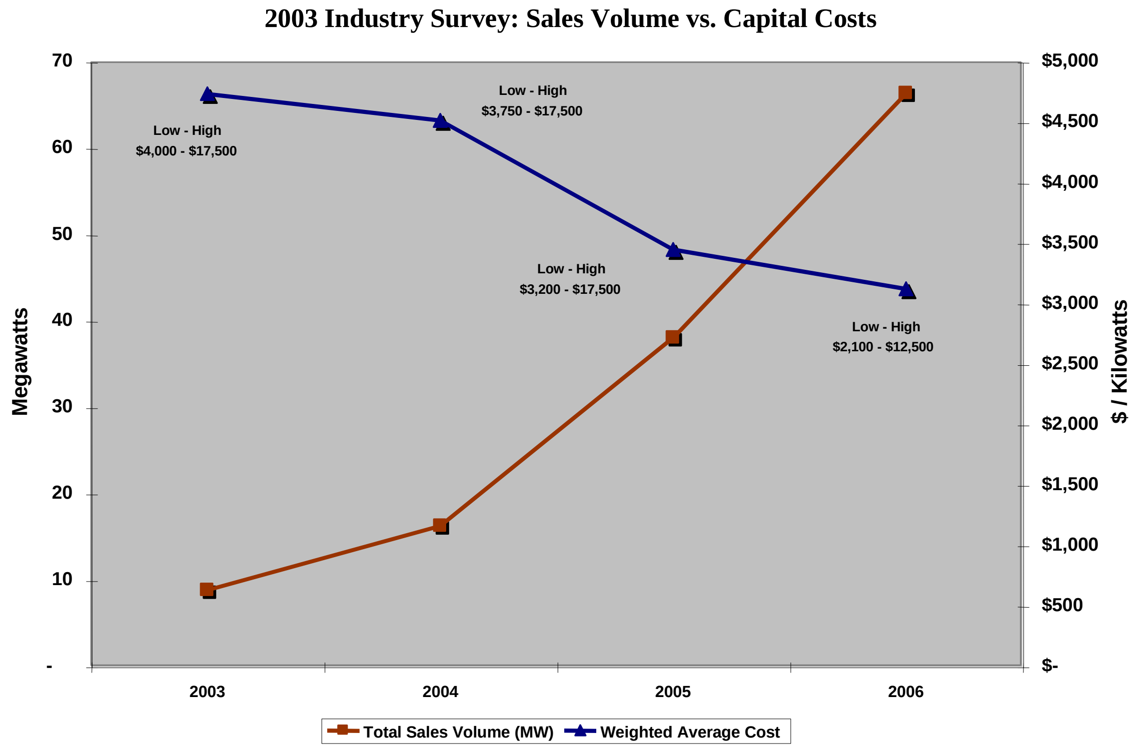


Figure 2: Projected fuel cell manufacturing capital costs versus sales volume

1.2 Description of the Internet accessible DG database

The DG database that was compiled in this task contains not only the economic parameters of fuel cells products and some competing DG products, but also a whole set of performance parameters that fully characterize the DG product.

Most of the DG product properties were extracted from the manufacturer's product specifications available on their web sites. In order to populate the database with additional economic, part load performance, and emissions parameters, which are not usually found in the product specifications, manufacturers were contacted and asked to review and complete their product database table. As of this writing, we have not received the manufacturer's feedback.

The database was designed and created in SQL language and a database-driven web site was developed to allow the user to compare different DG products and perform queries using key parameters such as: DG type, rated power capacity, DG manufacturer, emissions footprint, etc. The design phase of the SQL involved the selection of an appropriate set of parameters for the DG products as well as the proper definition of field formats for each of those parameters. The UCI Advanced Power and Energy Program webmaster developed a professional, user-friendly design for the databases.

The main website for this task presents a list of all the DG products selected, including all the fuel cell commercial products, all the MTG commercial products, and the products of three important manufacturers of photovoltaic modules. This list shows all the DG products in alphabetical order along with key parameters such the DG type, DG manufacturer's name, DG location, DG model name, and DG power capacity. Figure 3 shows a snapshot of this main website.


APEP / NFCRC / UCICL / UCI-ENG SCHOOL

Economics of Distributed Generation

Advanced Power & Energy Program
University of California, Irvine

Home / View California FC Installations / View Distributed Generation Products / Search Generator Products DB / Admin

Database List: Distributed Generation Products

Listings

View	DG Type	Manufacturer	Manufacturer Location	Model	DG Output (kW)
View Details	FC-MCFC	FuelCell Energy	Danbury, Connnecticut	DFC®300A	250
View Details	FC-MCFC	FuelCell Energy	Danbury, Connnecticut	DFC®1500	1000
View Details	FC-MCFC	FuelCell Energy	Danbury, Connnecticut	DFC®3000	2000
View Details	FC-PAFC	UTC Fuel Cells	South Windsor, Connecticut	PureCellTM 200	200
View Details	FC-PEMFC	Ballard	Burnaby, British Columbia	AirGenTM	1
View Details	FC-PEMFC	Ballard	Burnaby, British Columbia	Nexa®	1.2
View Details	FC-PEMFC	Plug Power	Latham, New York	GenSysTM	4
View Details	FC-PEMFC	Plug Power	Latham, New York	GenCoreTM	5

Figure 3: Snapshot of the website with the database list of DG products

The whole list of DG products and the rest of columns is reproduced below in Table 1.

Table 1: List of DG products and power outputs

DG Type	Manufacturer	Model	Location Manufacturer	DG Output (kW)
FC-MCFC	FuelCell Energy	DFC®300A	Danbury, Connecticut	250
FC-MCFC	FuelCell Energy	DFC®1500	Danbury, Connecticut	1000
FC-MCFC	FuelCell Energy	DFC®3000	Danbury, Connecticut	2000
FC-PAFC	UTC Fuel Cells	PureCellTM 200	South Windsor, Connecticut	200
FC-PEMFC	Ballard	AirGenTM	Burnaby, British Columbia	1
FC-PEMFC	Ballard	Nexa®	Burnaby, British Columbia	1.2
FC-PEMFC	Plug Power	GenSysTM	Latham, New York	4
FC-PEMFC	Plug Power	GenCoreTM	Latham, New York	5

DG Type	Manufacturer	Model	Location Manufacturer	DG Output (kW)
FC-PEMFC	Nuvera	AvantiTM	Cambridge, Massachusetts	3.7
FC-SOFC	Siemens-Westinghouse		Pittsburgh, PA	250
MTG	Capstone	C30	Chatsworth, California	30
MTG	Capstone	C30 biogas	Chatsworth, California	30
MTG	Capstone	C30 liquid fuel	Chatsworth, California	29
MTG	Capstone	C60	Chatsworth, California	60
MTG	Capstone	C60CHP	Chatsworth, California	60
MTG	Bowman	TurboGen TM TG80RC-G	Southampton, Hampshire, UK	80
MTG	Bowman	TurboGen TM TG80SO-G	Southampton, Hampshire, UK	80
MTG	Elliot Microturbines	TA-100 CHP	Stuart, FL, US	100
MTG	Ingersoll Rand Power Works	MT70	Portsmouth, New Hampshire	70
PV	United Solar Ovonic	PVL-128	San Diego, CA	0.128
PV	United Solar Ovonic	PVL-116	San Diego, CA	0.116
PV	United Solar Ovonic	PVL-87	San Diego, CA	0.87
PV	United Solar Ovonic	PVL-64	San Diego, CA	0.64
PV	BP Solar	BP 3160	Linthicum, Maryland	0.16
PV	BP Solar	BP 380	Linthicum, Maryland	0.08
PV	BP Solar	BP 3125	Linthicum, Maryland	0.125
PV	BP Solar	BP 585	Linthicum, Maryland	0.085
PV	BP Solar	BP 4160	Linthicum, Maryland	0.17
PV	Shell Solar	Shell SQ70	Amsterdam, The Netherlands	0.07
PV	Shell Solar	Shell SQ75	Amsterdam, The Netherlands	0.075
PV	Shell Solar	Shell SQ80	Amsterdam, The Netherlands	0.08
PV	Shell Solar	ShellSQ140-PC	Amsterdam, The Netherlands	0.14
PV	Shell Solar	ShellSQ150-PC	Amsterdam, The Netherlands	0.15
PV	Shell Solar	ShellSQ160-PC	Amsterdam, The Netherlands	0.16
PV	Shell Solar	Shell SM50-H	Amsterdam, The Netherlands	0.05
PV	Shell Solar	Shell SM55	Amsterdam, The Netherlands	0.055
PV	Shell Solar	Shell SM110-12P	Amsterdam, The Netherlands	0.11
PV	Shell Solar	Shell SM110-24P	Amsterdam, The Netherlands	0.11
PV	Shell Solar	Shell ST5	Amsterdam, The Netherlands	0.005
PV	Shell Solar	Shell ST10	Amsterdam, The Netherlands	0.01
PV	Shell Solar	Shell ST20	Amsterdam, The Netherlands	0.02
PV	Shell Solar	Shell ST36	Amsterdam, The Netherlands	0.036
PV	Shell Solar	Shell ST40	Amsterdam, The Netherlands	0.04

The user can obtain further details of each DG product by clicking in “View Details” link, in the first column of the main table. The comprehensive list of all the parameters included in the characterization of each DG product is presented in Table 2. The web site is not open to the general public yet, but it can be accessed.[1]

Table 2: List of DG parameters included in the database

DG Type/Manufacturer/ Location	Output/Dimensions
• DG Type • Manufacturer • Manufacturer location • Model • Targeted market sectors • Stage of development	• Output • Length • Width • Height • Weight
Economic Data	**Emissions (lb/MWh)**
• Capital costs • Installation costs • Installation cogeneration costs • Variable Operating & Maintenance costs • Fixed Operating & Maintenance costs	• CO_2 Emissions • CO Emissions • VOC Emissions • SOx Emissions • PM Emissions • NOx Emissions
Performance	**Temperature/Altitude Parameters**
• Heat rate • Hours between overhauls • Primary fuel type • Overall efficiency (LHV) • Electrical efficiency (LHV) • Minimum run time	• Rated temperature • Temperature coefficient • Rated altitude • Altitude coefficient
Part Load Ratio	**Part Load Cogeneration**
• Load Ratio 25% • Load Ratio 50% • Load Ratio 75% • Load Ratio 100%	• Cogeneration Ratio 25% • Cogeneration Ratio 50% • Cogeneration Ratio 75% • Cogeneration Ratio 100%
Exhaust flow at part load	**Exhaust Energy at part load**
• Exhaust flow at 25% • Exhaust flow at 50% • Exhaust flow at 75% • Exhaust flow at 100%	• Exhaust energy at 25% • Exhaust energy at 50% • Exhaust energy at 75% • Exhaust energy at 100%

[1] http://www.apep.uci.edu/DER/edg/Search/Alldb.aspx

Exhaust temperature at part load	Photovoltaic arrays Specifications
• Exhaust temperature at 25% • Exhaust temperature at 50% • Exhaust temperature at 75% • Exhaust temperature at 100%	• Photovoltaic type • Voltage at maximum power • Current at maximum power • Short circuit current • Open circuit voltage
• Heat exchanger temperature difference • Number of hours of fleet operation • Noise level	

The NFCRC continues to update and expand the database of DG products as new products are deployed in the US market and capital costs change.

3. TASK 2: REVIEW OF CASE STUDIES

This element consists of a review of case studies for installations of fuel cells throughout California. Firstly, a comprehensive Internet and literature search was performed to gather as much information as possible relevant to the installation and operational history of case studies in California. Second, a template with the set of descriptive, operational, and economic parameters for each site was developed and, in parallel, a SQL database was constructed with all the parameter fields identified previously. Third, the database was populated with the compiled information from the search phase. Finally, a draft version of the case studies was sent to key representatives for each site for them to review and complete the database.

1.3 Internet and literature search of fuel cells installations

A thorough Internet and literature search of fuel cell installations in California confirmed the hypothesis that no institution is compiling detailed information on fuel cell installations within the state. Therefore, the present product is original and will serve well the goal of the California Stationary Fuel Cell Collaborative to promote fuel cell commercialization.

Only one web site[2] was identified to provide some limited information on all the current fuel cell sites in California. In one link of the website[3] an incomplete list of 12 names is presented that corresponds to fuel cell installations in California. Some of the installations have links to other websites with more details. No extra data are provided for the fuel cell sites. It is not clear when the web site was last updated. In another link of the same web site, an updated (2/04) list of worldwide fuel cell installations is presented. The parameters included in the table are: Fuel cell Manufacturer, Project Partners, Fuel cell, Location, Building, Start date, Status, Fuel used, Picture, and Comments/Contact information. Out of the 316 fuel cells worldwide installations listed in this table, 30 are, were (already decommissioned), or will be installed in California.

[2] www.fuelcells.org
[3] (http://www.fuelcells.org/Installations/CA.htm)

The website[4] with the largest level of detail for fuel cell installations in California summarizes the Department of Defense (DoD) fuel cell programs which are managed by the U.S. Army Engineer Research and Development Center (ERDC)/Construction Engineering Research Laboratory (CERL). Three of the fuel cell demonstration activities, the PAFC Demonstration Program, the ongoing Residential Demonstration Program, and Climate Change Rebate Program, have contributed to the fuel cell installations in California. The PAFC Demonstration Program involved 5 different sites in US military bases in California. The Climate Change Rebate Program has funded the demonstration of 6 fuel cell commercial sites in California since 1995. The Residential Demonstration Program has funded only one PEM fuel cell demonstration on a California US military base, but up to 45 PEM fuel cells have been deployed in other military bases throughout the US. These three programs are very well documented, including detailed information of each demonstration site. The parameters that are presented for each site are the following:

- Site Description
- Location
- Fuel Cell Start-up Date
- Operating Status
- Building Application
- Thermal Application
- Thermal Utilization
- Stand Alone Operation (YES/NO?)
- Estimated Savings
- Hours of Operation
- Total Electric Output (MWh)
- Average Power Output (kW)
- Total Heat Recovered (MMBtu)
- Heat Recovery Rate (kBtu/h)
- Input Fuel (ft^3)
- Electric Efficiency
- Thermal Efficiency
- Total Efficiency
- Capacity Factor
- Availability

Some of the demonstration sites also include as well a Site Evaluation Report with further analysis.

Many other minor web sites were found and analyzed. Most contain information regarding a particular fuel cell case and provide only a succinct summary of the installation, including generally a picture, the name of the site, the type and capacity of the fuel cell, and in same cases the thermal application of the waste heat. All these web links were also compiled in the database so that the user can click the link in the detailed information web site and consult the original source.

1.4 Database Template for Fuel Cell Case Studies in California

Building upon the parameters presented in the DoD web site for fuel cell demonstrations, we developed a SQL database template to be populated with operational and economic data for all the fuel cell installations in California. In parallel, a database-driven web site was constructed so that the information compiled in the database can be retrieved worldwide.

The database parameters selected to thoroughly characterize each fuel cell installation in California are presented in Table 3.

[4] www.dodfuelcell.com

Table 3: List of parameters included in the database for the fuel cell case studies in California

• Location	• Altitude	• Climate Zone
• Site Specifications		
• Fuel Cell Capacity	• No of Units	
• Fuel Cell Type	• Fuel Cell Manufacturer	• Fuel Cell Model
• Application		
• Project Participants		
• Date Start Up	• Date Shut Down	
• Public Documents		
• Other Unique Features		
• Purchase Cost of Fuel Cell	• Installation Cost	
• Applicable Subsidies		
• Electric Utility	• Gas Utility	
• Electric Rate	• Gas Rate	• Operating Hours
• Electricity Output (MGWh)	• Average Power	• Electric Efficiency (based on HHV)
• Overall Efficiency	• Availability	• Annual Savings
• Installation Web Site		

The web site[5] for the fuel cell case studies in California consists of a summary page, where the main features of all the California installations are presented, including the Host Organization, Location, Fuel Cell Type, No. of Units, and Capacity. This web site is not yet open to the public. In a similar way to what it is implemented for Task 1 web site, the user can access the detailed parameters presented in Table 3 by clicking in the first column of the summary list. Figure 4 shows a snapshot of the summary web page.

[5] http://www.apep.uci.edu/DER/edg/Installations/Index.aspx


APEP / NFCRC / UCICL / UCI-ENG SCHOOL

Economics of Distributed Generation

Advanced Power & Energy Program
University of California, Irvine

Home / View California FC Installations / View Distributed Generation Products / Search Generator Products DB / Admin

Active Fuel Cell Installations

Click on view to see fuel cell installations details

Details	Host Organization	Location	Fuel Cell Type	No. of Units	Capacity (kW)
View	AB Parking Facilities	Fresno, CA	PAFC	3	200
View	Chevron Texaco Corporate Data Center	San Ramon, CA		1	200
View	Edwards Air Force Base	Edwards Air Force Base, Palmdale, CA	PAFC	1	200
View	Ford Premier Group Design Center, North American Headquarters of Ford Motor Co.	Irvine, CA	PAFC	1	200
View	LA Dept. of Water & Power	Playa Vista, CA	PAFC	1	200
View	LADWP Headquarters John Ferraro Building	Los Angeles, CA	MCFC	1	250
View	Naval Construction Battalion	Port Hueneme, CA	PAFC	1	200
View	Port of Los Angeles, Terminal Island	San Pedro, CA	MCFC	1	250
View	Sierra Army Depot	Herlong, CA	PEMFC	1	4.5
View	South Coast Air Quality Management District Headquarters	Diamond Bar, CA	PAFC	1	200
View	The Presidio	San Francisco, CA	SOFC	1	5
View	Rancho Las Virgenes Composting Facility	Calabasas, CA	PAFC	2	200

Figure 4: Snapshot of the website with the database list of fuel cell installations in California.

The database is designed in a flexible way so that it can be readily modified or expanded by the authorized user from a MS Access interface, with no required changes in the database or web site code.

1.5 List of fuel cell installations in California

The list of fuel cell case studies in California was divided in two categories according to the criteria of status of operation. The first demonstrations for phosphoric acid fuel cells were installed in California in the early nineties. Once they reached the end of their projected lifecycle, they were shut down and they are not operating any more. Moreover, a few more recent demonstration projects with other fuel cell types were also shut down after a few years of testing. However, their accumulated operational history is still useful and, therefore, it is retained under the category of "inactive" fuel cell installations. The rest of fuel cell power plants that are still operating are classified as "active" installations.

The list of old fuel cell installations that are already dismantled is shown below. In parenthesis we include the fuel cell type and the shut down date:

- Irvine Hyatt Regency Hotel, Irvine, CA (PAFC, March, 2002)
- Kaiser Permanente Riverside Medical Center, Riverside, CA (PAFC, February, 2000)
- Kaiser Permanente Hospital, Anaheim, CA (PAFC, May, 2000)
- Santa Barbara Jail, Santa Barbara, CA (PAFC, March, 2001)

- University of California Santa Barbara, Santa Barbara, CA (PAFC, June, 1998)
- Scott Receiving Station, Santa Clara, CA (MCFC, May, 2000)
- Kraft Foods, Buena Park, CA (PAFC, June, 1996)
- Naval Hospital Marine Corps Base Camp Pendleton, Oceanside & Fallbrook, CA (PAFC, January, 2002)
- Naval Hospital MCAGCC Twentynine Palms, Twentynine Palms, CA (PAFC, May, 200)
- Vanderberg Air Force Base, Lompoc, CA (PAFC, September, 1994)
- Nextel, northern California (PEMFC, September, 2003)

The rest of the list consists of fuel cell installations in California that are still in operation or that are to be commissioned in the near future. The list below corresponds to this second category of "active" fuel cell installations.

- Naval Construction Battalion, Port Hueneme, CA
- Edwards Air Force Base, Edwards Air Force Base, CA
- South Coast Air Quality Management District Headquarters, Diamond Bar, CA
- Chevron Texaco Corporate Data Center, San Ramon, CA
- LADWP Headquarters John Ferraro Building, Los Angeles, CA
- Port of Los Angeles, Terminal Island, San Pedro, CA
- Sierra Army Depot, Herlong, CA
- Ford Premier Group Design Center, North American Headquarters of Ford Motor Co., Irvine, CA
- AB Parking Facilities, Fresno, CA
- The Rancho Las Virgenes Composting Facility, Calabasas, CA
- LA Dept. of Water & Power, Playa Vista, CA
- The Presidio, San Francisco, CA
- Naval Station North Island and Submarine Base, San Diego, CA
- Naval Air Weapons Station, China Lake, CA
- National Fuel Cell Research Center, Irvine, CA (25 kW SOFC)
- National Fuel Cell Research Center, Irvine, CA (220 kW Hybrid)
- National Fuel Cell Research Center, Irvine, CA (5 kW PEMFC)

The database for fuel cell case studies in California contains to date 29 entries, including both the active and the inactive fuel cell installation categories. If the list of 29 fuel cell installations in California is compared with the information provided by the U.S. Fuel Cell Council,[1] 30 different installations are represented in California. The reasons for the difference are (1) two entries by the U.S. Fuel Cell Council that do not correspond with actual fuel cell sites, and (2) the absence of an operating site. The first one of the two are two 5 kW SOFC CHP units in Yosemite National Park that were never installed. The second of the two is the recently announced (November, 2003) Stuart Energy contract from the South Coast Air Quality District to develop a Hydrogen Energy Station with both vehicle fueling and power generation capabilities in southern California. The 120 kW power module is not a fuel cell but a hydrogen-powered internal combustion engine generator set. Therefore, neither of these sites is included in the current effort. The site excluded by the U.S. Fuel Cell Council is a 5 kW PEMFC, which started test operation in September 2003 at the NFCRC.

4. TASK 3: REVIEW OF ECONOMIC CRITERIA AND LITERATURE

A thorough literature and Internet search was conducted to identify and evaluate economic tools for distributed generation/combined heat and power systems, in general, and fuel cells, in particular. Table 4 shows a summary with the list of DG economic tools that were analyzed. The summary includes the name of the calculator and its developers, the data libraries included, the financial output parameters, whether or not a tool to estimate building energy consumptions is available, the platform under which the tool was developed, and finally some comments on positive and negative points.

Table 4: List of DG economic tools

Name	Data libraries included	Economic performance parameters	Building Energy Simulation ?	Format	Comments
Distributed Generation Analysis Tool Developed by SAIC (Science Applications International Corporation), funded by US DOE	-2 PEM (2 kW and 350 kW) -1 PAFC 200 kW -1 MTG kW -1 NG ICE 350 kW	-Simple payback -Cash flow analysis -Return on investment	No, commercial or residential usage established by user	Ms Access	-Good, flexible tool, it can be extended easily. - Includes Generator Usage Plan (control) - Includes flexibility in Energy Rates - Includes flexibility in financial parameters - Includes emissions - Free
DE Calculator Developed by Consumer Energy Council of America (CECA)	600 products including ICE, MTG, GT and FC, PV, and wind. Data can be copied manually from web	None	No	Web access	- Simple but useful tool. No economic calculations included - Database driven query based on user requirements (Facility load, max site load, fuel type, technology, target installed cost, etc.) - Free
Spreadsheet for Evaluating Economics of CHP Systems Developed by the MidWest CHP center http://www.chpcentermw.org /html/10_library.html#tools	1 Generic Gas ICE 1 Generic GT 1 Generic MTG 1 Generic PAFC	- Annual savings - Simple payback period	No	Ms Excel with macros	- Simple but useful screening CHP tool - Includes absorption chillers and dessicants - Recommends generator capacity - Free - Only monthly average data as input
USFCC's Market Performance Model for Stationary Fuel Cell Applications Developed by SGA Energy Limited, funded by USFCC	No libraries FC data, loads, utility rates, and financial data defined by user	-Annual cost savings -Simple payback -NPV -IRR	No	Ms Excel with macros	- Useful screening tool for FC with thorough economic analysis - No load following scenarios - Extensive need for economic and performance data
Fuel Cell Evaluation Worksheet Developed by DoD Fuel Cell Program http://www.dodfuelcell.com/spreadsheet.html	No libraries Data defined by user Sample data for PAFC	- Annual savings - Simple payback period	No	Ms Excel with macros	- Simple but useful for preliminary evaluation of fuel cell feasibility - Free - Can be easily modified to account for waste heat cooling instead of waste heat for heating.

Name	Data libraries included	Economic performance parameters	Building Energy Simulation ?	Format	Comments
D-Gen Pro Developed by Architectural Energy Corporation, funded by Gas Technology Institute	- 27 DG equipment (NG ICE, GT, MTG and 1 FC) - Utility rates - Climate - 14 specific building types	-Simple payback -Life cycle analysis -Return on investment	Yes, hour-by-hour simulation of building, based on weather conditions, actual energy use, and load shapes	Stand alone application based on Ms Access	- 695$/license - Useful tool for CHP screening - Includes embedded DOE 2 building energy modeling - No cooling option - No hourly outputs - Limited flexibility to simulate buildings

After the analysis of the type of economic tools available in the literature, the authors identified a possible classification of these tools according to the level of detail at which the building integrated DG operation and the utility rate structures are evaluated:

1) Cost of electricity with assumed DG annual operation factors and average utility rates

This category corresponds to the simplest case in which the cost of electricity with the DG system or systems is compared with the average cost of electricity for the selected utility and selected market sector. The cost of on-site power is calculated as the ratio of levelized annual cost and the annual delivered good, namely, electricity. The levelized annual cost is obtained by multiplying the life cycle cost by the capital recovery factor for discount rate and system life. The mathematical formulation for these operations can be found in Rable and Fusaro's work [2].

The advantage of this method is the ease of calculation. However, when only a fraction of the electricity is generated on-site (which happens in most of cases), it is challenging to evaluate the cost of utility-furnished electricity. Depending on the accuracy of the assumptions made for DG capacity factors and waste heat recovery factors, the real cost of electricity could be very different from the approximated value resulting from this method. The information relating utility time-of-use pricing structures, building load profiles and DG operation is not required in this approach.

2) Annual energy savings with detailed time-of-use utility rate schedule but with no building energy load profiles data

This second category is a step further to achieve better accuracy in the calculated annual energy savings of the DG building integration. This method gives a precise prediction of the maximum annual savings achievable with the integrated DG system. First, the user must assume a predetermined basic DG schedule that is either a base load or a peaking operation. Then the detailed time-of-use rate structure is used to assess in an hourly basis how much money is saved due to the DG displacement of utility power demand and electricity. When DG fuel costs, DG operating and maintenance costs, DG standby charges (if any), and DG heat recovery benefits are added to the equation, one can determine the net savings for each hour of the year. The sum of the hourly results gives the annual savings due to DG implementation.

It is important to emphasize that this method is accurate as long as the facility has minimum thermal and electrical demands that exceed the DG outputs at all times. When this hypothesis is not true, the real DG savings cannot be evaluated using this approach. The actual hourly building energy profiles have to be considered and a more comprehensive strategy like the one presented below must be used.

3) Annual energy savings with detailed time of use utility rate schedule and building energy load profiles data

This method takes into account the actual energy loads of the building under study, the DG operation strategy selected to serve those loads, and the detailed time-of-use utility rate schedules for electricity and natural gas. All this information is accounted at a very high resolution, normally on an hourly basis or even less.

In a first step, natural gas and electricity consumptions of the commercial building are determined at an hourly resolution for the business-as-usual case or base case, in which the electric grid and the natural gas utility serve all the loads. Appling the corresponding electric and natural gas time-of-use rates, the energy bill for the base case is determined. Other possible outputs to be evaluated are the annual gas pollutant and greenhouse gas emissions associated to the calculated annual energy consumption. The hourly building electric and thermal profiles can either be measured or estimated using software tools for whole-building energy analysis such as DOE2.1-based eQUEST.

In a second step, the electrical generator is integrated in the selected building assuming a DG electric operation strategy and a heat recovery strategy (if CHP mode is available). Next, the energy bill is again calculated from the energy building simulation taking into account the utility rate structures.

Finally annual energy savings and bill savings are evaluated as a difference of base case utility bill and DG case utility bill plus DG annual operating and maintenance costs. This third type of economic tool is the most accurate, but also the most complex and time-demanding.

In the following two sections we describe two different economic calculator tools for DG systems that were developed under the framework of this project. The first one is a detailed tool that belongs to the third category alluded to above. The second one is more simplified and can be classified under the second category.

1.6 Fuel cell economics for commercial building integration

1.6.1 Introduction

Under the framework of the third element of this project we developed an interactive web site in order to present to the public the economic benefits, as well as the energy efficiency and environmental benefits of advanced DG systems (fuel cells, micro turbines, and photovoltaic arrays) when they are integrated into a commercial built environment. In this report, we present most of the information that is also available online, but also include further analysis and discussion for a subset of all the DG simulation cases conducted so far.

For this report, four generic types of commercial buildings (small office building, medium office building, hospital, and school) are selected and described and their typical energy consumption profiles are analyzed on the basis of their electric and gas hourly profiles for the peak electric day and the peak gas day. Next, a variety of high-efficiency technologies and practices that decrease the building annual bills, annual energy consumption and annual emissions are presented. These possibilities are: (1) the implementation of Energy Efficiency Measures (EEM); (2) the integration of DG, such as photovoltaic panels, fuel cells or microturbines; and (3) the substitution of the traditional cooling system by a thermally activated absorption cooling (AC) system to make better annual use of the waste heat. A total of 24 building simulation cases are run to analyze a wide variety of combinations of the above-mentioned strategies as well as the influence of the building location.

The same exact cases presented in this report are also available at a web site[6] That, while accessible, is under development. A query tool allows the user to pick up one building type and one or some of the building advanced energy options and evaluate the economic and environmental impacts in annual energy bills and emissions respectively when comparing the results with those for the same building without any advanced energy option. The latter is referred hereafter as the "base case" and serves as a reference or anchor case.

All the building results presented in this web site were generated using the public domain software eQUEST, which is a building energy simulation program that uses the most widely recognized and respected building analysis tool, DOE-2, as the simulation "engine". This program is able to calculate the hourly energy use and energy cost of several types of commercial buildings given information about the weather in the building location, construction, operation, utility rate schedule, heating, ventilating, air-conditioning (HVAC) equipment, as well as the DG unit performance parameters and operation strategy.

1.6.2 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 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. The same information can be found in the web site.

1.6.2.1 Office buildings

According to the Commercial Building Energy Consumption Survey, 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 percent of all commercial energy consumption. They use a total of 1.0 quadrillion Btu of combined site electricity, natural gas, fuel oil, and district steam or hot water. The relative weights of the different energy sources are: electricity: 66%, natural gas: 23%, district heat: 7%, and fuel oil:

[6] http://www.apep.uci.edu/DER/buildingintegration/

3%. In average, the distribution of energy end uses is: 48% HVAC, 29% lighting, 16% plug power, and 7% miscellaneous. The same distribution for a typical office building in Los Angeles area is: 35% HVAC, 30% lighting, 31% plug power, and 4% DHW [3].

The US 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-CHP technologies have electric to thermal ratios in the range of 0.5 to 2.5. Therefore, office buildings can only be 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-CHP technical potential (no economics considered) for all the office building applications in the US is about 18,000 MW [4] and the market potential (based on achievable economics) is 10,500 MW [5].

1.6.2.2 Health Care buildings

In the US, there are about 22,000 impatient health care buildings, 16,400 of those being hospitals and the rest psychiatric facilities and rehabilitation centers. The average inpatient hospital is about 74,600 square feet and all the inpatient health care buildings account for 1.6 billion square feet, which is about 3% of all commercial floor space in the U.S. Health care buildings (both outpatient and inpatient) account for the 11 percent of all commercial energy consumption, using a total of 561 trillion Btu of combined site electricity, natural gas, fuel oil, and district steam or hot water. They are the fourth highest consumer of total energy of all the building types. The relative weights of the different energy sources are: 38% electricity, 46% natural gas, 13% district heat, and 4% fuel oil. Looking at the distribution of energy end uses in US health care buildings, about half of the total energy is dedicated to HVAC (49%), whereas lighting, plug power, and miscellaneous uses account for 16%, 7%, and 28%, respectively [6]. In the Los Angeles area, similar average energy end use values exist (44% HVAC, 26% lighting, and 30% plug power) [3].

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 CHP technologies, even in the case where only DHW demands are met by CHP. The estimated DG-CHP technical potential for all the inpatient health care applications in the US is about 8,400 MW [4] and the market potential is above 7,000 MW [5]. In California the technical potential reaches 300 MW [7].

1.6.2.3 Education Buildings

Education buildings are the fifth most prevalent commercial building type in the US, with about 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 25,100 square feet per building, and they account for the 13% of all the commercial floor space. They consume a total of 614 trillion Btu of energy, with the following distribution among of energy sources: 36% electricity, 40% natural gas, 15% district heat, and 9% fuel oil. 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. The majority of energy use in education buildings is for space heating (41%), with lighting (20%) and water heating (22%) about equal as the next most energy-consuming uses, and followed by miscellaneous uses (11%), and cooling (6%) [6]. The typical energy use distribution for a school in LA area with nine months of occupancy is: lighting 39%, HVAC 25%, DHW 13%, and plug power 23% [3].

Educational buildings present a favorable electric to total thermal ratio of 0.67 for a DG-CHP system to be integrated. 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-CHP 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 CHP technical potential for schools only is about 15 GW and reaches 18 MW if colleges and universities are included [4], with more than 10 GW of real market potential [5]. The CHP technical potential for educational buildings only in California is 2. GW.

1.6.3 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 50,000 square feet 2-story office building, with typical characteristics for these types of building, including administrative office schedules and rather low base electric load, is called Small Office Building (SOB). A second 2-story office building with almost double floor space (90,000 sqf) and the same typical features as the first one, but relatively higher base electric load, is called Medium Office Building (MOB). As a typical example of a health care building a 250,000 square feet 10-story hospital (HOSP) was chosen. The fourth building selected is a 250,000 sqf 4-story school/college, which is abbreviated by COLL.

In most cases we used the default parameters provided by eQuest 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-vs.-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 2 more differentiated office buildings.

All buildings were assumed to be located in the Los Angeles area 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 the type of building and his location. Complex time-of-use electric tariffs whose energy and demand charges vary by time of day (peak, mid-peak, off-peak, etc.) were assigned to both the 2 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 in 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 of MTG in southern California [8]. Electric and natural prices are to be reviewed periodically and the economic results for DG building integration updated in the web site. A few cases for the small office-building template were run with Boston (MA) weather conditions and the most updated utility tariffs for these cases 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 rates about 100% higher than the corresponding Los Angeles rates considered for the same small office building, both circumstances unfavorable for the economics of gas-driven DG-CHP technologies.

Table 5 summarizes the main characteristics of the four selected commercial building templates including building code, building description, square footage, 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 1 unit of electricity 5 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 now the office buildings and the college more compatible with DG-CHP technologies.

Table 5: Main characteristics of selected commercial building templates

Building Code	Description	Square footage	No floors	HVAC System	Base power demand	Average Power demand	Peak Power Demand	Annual E/T ratio	Annual E/T ratio with AC
		(Ft^2)			(kW)	(kW)	(kW)		
SOB	Small Office Building Base Case	50,000	2	Packaged single zone DX coils, with Furnace	11	55	270	31.7	0.45
MOB	Medium Office Building Base Case	90,000	2	Packaged single zone DX coils, with Furnace	100	165	460	44.9	0.45
HOSP	Hospital Base Case	250,000	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	250,000	4	Packaged single zone DX coils, with Furnace	70	370	1450	11.5	0.44

1.6.4 Energy Efficiency Measures (EEM)

The first consideration before attempting a DG building integration is to maximize the 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 [9].

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 [3]. The set of energy efficient strategies introduced in each building category are presented in Table 6. Although simulation results of EEM cases compared to the base cases are not shown in this report, they consistently illustrate a 5 to 20% annual reduction in electricity consumption, greenhouse CO_2 gas and gas pollutant NOx emissions, and utility costs. The rest of the energy simulation results with DG systems and with absorption chillers described below will be compared with the EEM cases.

Table 6: Set of Energy Efficiency Measures (EEM) implemented for each building type.

Type of building	**Energy Efficiency Measures**
Office buildings	• Windows exterior shading (overhangs) • Day lighting controls • 15% increase in HVAC cooling efficiency
Hospital	• 4 °F lower condenser water temperatures • 15% increase in HVAC cooling efficiency
College	• Windows exterior shading (overhangs) • Day lighting controls • 15% increase in HVAC cooling efficiency

1.6.5 Characteristics of selected DG types

The traditional and mostly adopted DG technologies in the current electric generation market are internal combustion engines (ICE) and gas turbines (GT). However, in this work we considered three advanced DG types that are just starting to get a share in the market, presenting potential environmental and energy-efficiency benefits over the traditional systems. These advanced types are fuel cells, micro turbines (MTGs), and photovoltaic (PV) solar panels. Fuel cells and micro turbines are fuel-driven electric generators particularly well suited for the integration into the built environment because they can serve small load demands, have high overall efficiency in cogeneration applications, and present low emission factors. Photovoltaic panels are a solar-driven, renewable energy with no emissions and can be easily mounted on the roof of the buildings, but they only can produce electric power, with no heat recovery option.

Although capital costs for PV panels and fuel cells are relatively high, they can be cost-effective in particularly well-suited applications or in cases where public rebates are offered. MTGs have more competitive capital costs providing short return-on-investment periods in locations with high electricity prices and cheap gas rates such as California, especially in applications where the waste heat can be fully utilized.

For this study we considered generic units for each DG type having specific power capacities, electric and overall efficiencies, performance parameters, and economic data, as shown in Table 7. The fuel cell is a high temperature fuel cell (HTFC) of 250 kW, the MTG is a 60 kW MTG and the PV unit is a 60 kW array of high-efficient multi-crystalline silicon. 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 [10], and authors' understanding of these technologies for the latter. For the 60 kW PV unit, the generic built-in PV module available in eQUEST was applied. The units selected do not represent any particular manufacturer product. Thus, results presented in this report can be extended to any unit with similar characteristics to the generic ones considered in this analysis.

Table 7: Main characteristics of selected DG generic units

DG Code	Description	Load	Electric Efficiency	Overall Efficiency	E/T Ratio	Start-up time	Minimum ratio	Operating mode	O&M costs	Capital cost
		(kW)				(s)			($/kWh)	($/kW)
HTFC	Generic high temperature fuel cell	250	47%	85%	1.2	36*	0.3	Tracking electrical load	0.007	3,000**
MTG	Generic micro turbine	60	23%	71%	0.5	72	0.2	Tracking electrical load	0.01	1,000
PV	Generic photovoltaic panel	60	11.8%	11.8%	-	-	0.02	Tracking electrical load	-	6,000**

* Assuming that the FC works in stand-by mode
** Including rebates

1.6.6 Characteristics of Absorption Cooling

In our analysis of DG integration into the built environment in California, we included absorption cooling 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-CHP 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.

Absorption chillers use thermal energy instead of mechanical energy to provide cooling or refrigeration and, therefore, they can be powered by lower cost fuel or waste heat. Heat required for the chiller is typically provided by steam, water from a boiler or combustion turbine, or even direct exhaust gases, but also can be provided by an integral, direct gas-fired heater. Other energy use occurs in pumping fluids around the process, pumping condenser water, and driving cooling tower fans. Cooling towers are larger with absorption chillers than with electrical chillers because they have to reject the cooling load plus the input heat to drive the process.

Absorption chillers involve a complex cycle of absorbing heat from a driving source to create chilled water. Steam, or hot water from a boiler or from a heat recovery unit, is used to boil a solution of refrigerant/absorbent, most systems using water/lithium bromide for chilling and ammonia/water for refrigeration as the working solutions. The absorption chiller then captures the refrigerant vapor from the boiling process, and uses the energy in this fluid to chill water after a series of condensing, evaporating, absorbing steps are performed. This process is essentially a thermal compressor, which replaces the electrical compressor in a conventional electric chiller. In doing so, the electrical requirements are significantly reduced, requiring electricity only to drive the pumps that circulate the solution.

The process described above is employed by single-effect chillers. Two types of absorption chillers are commercially available: single- and double-effect systems. Triple-effect systems are under development. In multi-effect systems, higher temperature heat drives the first stage or effect, and heat off the first stage is used to drive a second stage or effect, increasing the overall efficiency. Single-effect units offer coefficient of performances (COPs) of about 0.7, which means that 7 units of cooling are produced for every 10 units of waste heat recovered. Double-effect units add another boiling and condensing step at higher temperature, thus attaining higher COPs of about 1.1. This means that the cooling tower required for a double-effect chiller is smaller than for a single-effect chiller (by about 40%).

In the building simulations presented in this work we always used a hot water, indirect fired double-effect absorption chillers for the building energy simulations with enough cooling capacity to serve the peak cooling demands of the building considered. 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 chiller were used. As capital and operating and maintenance costs of the absorption chiller system varies with the cooling capacity of the unit, 2 different set of cost were considered in the simulations: $950/ton (capital cost, including cooling tower, pump, and piping) and $38/ton (O&M) for the 2 office buildings; and $700/ton and $25/ton for the hospital and the college building templates, which require larger cooling capacities [11].

1.6.7 Building simulation assumptions

Although some of the common consideration and assumptions made in the simulations were already mentioned above, we include them all in this section in a list format:

- 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 tracking 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.

- No waste heat storage is contemplated. 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 more efficient, double-effect absorption chillers.
- No stand-by charges for DG systems are included in utility rates.

1.6.8 Building simulation parameters

Among the huge amount of data coming from the eQUEST output report for one building energy simulation, only a few parameters were considered, which condense the main environmental and economic impacts of the DG integration into the built-environment. These building impacts include electricity and gas consumption, primary energy consumption, CO_2 and NOx emissions resulting from the consumption of that energy, DG unit utilization factor, capacity factor and heat recovery factor, electric and natural gas utility costs and operating and maintenance costs, and cost savings, all of them in 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 come directly from the simulations, and others need to be post-processed based upon eQUEST output results. Those parameters that need further explanation to be thoroughly defined are presented 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 US average 30% electric efficiency for power production was applied [CEC, 1999 #4].
- **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 8 [12].
- 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 of that year. Note that with this definition a 100% utilization means the unit was running all year, but no information is given about 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 or equal than 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 is the heat recovery factor, the higher the overall efficiency of the building-integrated DG and more profitable the DG investment.
- **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 is achieved every year, without taking into account inflation or time-value of money. It is determined as the ratio of the capital cost of the DG units and the absorption unit, and the first year energy cost savings.

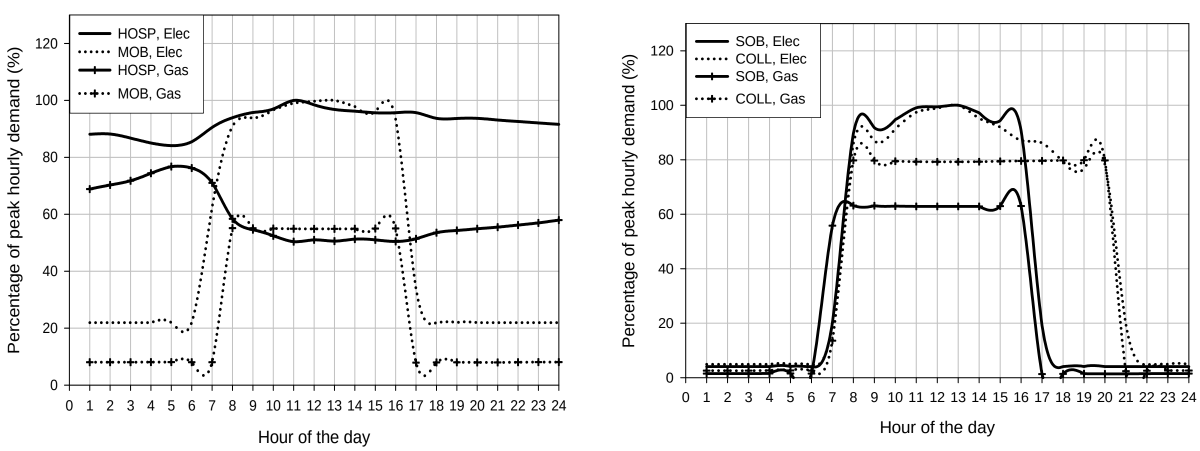
Table 8: Efficiency, CO_2 and NO_x emissions factors for the average US grid, a typical boiler, a HTFC, a MTG, and a PV unit.

	NO_x	CO_2	Electric Efficiency
	(Lbs/kWh)	(Lbs/kWh)	(%)
US Grid	$3.43\ 10^{-3}$	1.34	30
Boiler*	$5.02\ 10^{-4}$	0.403	85
MTG	$7.0\ 10^{-4}$	1.50	27
HTFC	$7.0\ 10^{-5}$	0.85	47
PV	0	0	12

* Units in pounds per kWh of natural gas in the boiler

1.6.9 Load profile engineering of base cases

In this section the hourly electrical and gas load shapes in the peak electric day and the peak gas day for the four selected buildings in Los Angeles are presented and discussed. These load shapes are the basis for understanding the annual building results that are shown below. The load shapes were produced running the DOE-2-derived building model for each base case building. In order to plot all shapes in the same scale, hourly profiles are shown as percentages of the peak hourly load, which for electricity takes places in a day of August, and for natural gas occurs in January. Figure 5 shows the electric and natural gas hourly loads in the peak electric day for the four commercial building templates considered and Figure 6 presents the same loads for the peak gas day.



(a) *(b)*

Figure 5: Electric and natural gas hourly profiles for the peak electric day. (a) Hospital and Medium office building load shapes; (b) Small office building and college/school load shapes.

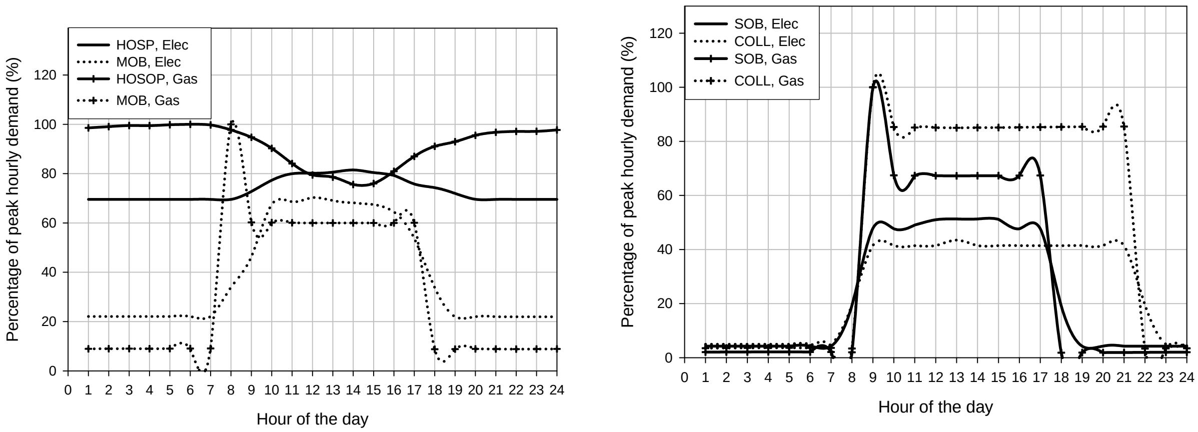


Figure 6: Electric and natural gas hourly profiles for the peak natural gas day. (a) Hospital and medium office building load shapes; (b) Small office building and college/school load shapes.

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 all 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). Those ratios are very well matched with the DG/CHP types in study (E/T HTFC: 1.2, E/T MTG: 0.5). Thus, the hospital template is a perfect candidate for the integration of DG with CHP, even without the consideration of absorption cooling to increase thermal loads.

The two office buildings have very similar electric and 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 modified non-occupancy loads. The electric load in the peak electric day reaches a practically flat maximum during typical working hours (7-8 to 16-17), whose interval is slightly reduced (9-10 to 16-17) in the gas peak day due mainly to the decrease in cooling loads. Although the thermal gas loads of the office templates are very coincident to the electrical load, which is ideal for CHP, the amount of heat needed 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 rest of gas loads are for DHW. Thus, only a small fraction of the waste heat rejected by the DG-CHP unit tracking electric load could be used in traditional thermal loads, and their 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 those buildings much better candidates for a cost-effective DG-CHP 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 very well matched with the electric load shape. The electric to thermal ratios both in summer (22) and winter peaks (16) are about 3-fold lower than the ones for the office buildings, but they are still too high to match the DG-CHP power and heat co-production ratios well, and most of the available waste heat would be lost if no additional thermal demands are required.

1.6.10 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 9 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 web site has 14 additional cases that are not analyzed in this report. As alluded to previously, the database-driven web site will be updated periodically and more DG cases will be added. Furthermore, the user, through the interactive query tools available in the web site, should be able to reproduce online all the figures shown below.

Table 9: List of simulated base cases and DG building integration cases.

Case Code	Description	Primary Energy Consumption.	CO_2 Emiss.	NOx Emiss.	DG Utilization factor	Heat Reco-very factor	Electric Bill	Natural Gas Bill	O&M costs for DG and AC	Pay back period
		(GWh/year)	Tons/year	Lbs/year	(%)	(s)	(k$/year)	(k$/year)	(k$/year)	(years)
SOB	2-story office building, 53,520 sqf	1.64	300	1,679	—	—	88.5	0.8	—	—
MOB	2-story office building, 90,000 sqf	4.87	889	4,986	—	—	223	1.5	—	—
HOSP	10-story hospital,	46.61	8507	40,407	—	—	1,242	227.0	—	—
COLL	4-story school/college,	11.19	2041	11,289	—	—	622	8.7	—	—
SOB EEM	SOB + EEM	1.40	255	1,425	—	—	74	0.8	—	—
MOB EEM	MOB + EEM	4.49	818	4,588	—	—	202	1.5	—	—
HOSP EEM	HOSP + EEM	45.57	8316	39,332	—	—	1,200	227.0	—	—
COLL EEM	COLL + EEM	9.32	1700	9,366	—	—	500	8.7	—	—
MOB HTFC	MOB EEM + 1HTFC	3.13	896	1,281	100	3	32.2	48.2	8.4	6.6
MOB HTFC AC	MOB EEM + 1HTFC+AC	3.55	977.4	1,281	100	47	5.3	60.7	16.9	8.0
HOSP 4HTFC	HOSP EEM + 4HTFC	26.0	7,231	11,215	98	85	134.8	368.7	59.5	3.5
COLL HTFC	COLL EEM + 4HTFC	7.8	1,700	6,604	47	37	343.8	38.1	6.6	6.3

Case Code	Description	Primary Energy Consumption.	CO_2 Emiss.	NOx Emiss.	DG Utilization factor	Heat Reco-very factor	Electric Bill	Natural Gas Bill	O&M costs for DG and AC	Pay back period
		(GWh/year)	Tons/year	Lbs/year	(%)	(s)	(k$/year)	(k$/year)	(k$/year)	(years)
COLL HTFC AC	COLL EEM + 4HTFC+AC	9.9	2,382	8,108	47	97	257.1	106.3	25.2	10.6
SOB MTG	SOB_EEM + 1MTG	1.57	262	979	32	4	47	14.7	1.6	5.1
SOB MTG AC	SOB_EEM + 1MTG+AC	1.77	300	1,037	32	90	38.1	20.4	6.7	19
MOB 2MTG	MOB_EEM + 2MTG	5.65	877	2,001	100	2	79.3	73.5	9.4	2.9
MOB 2MTG AC	MOB_EEM + 2MTG+AC	5.89	920	1,981	100	30	56.6	81.6	17.6	7.0
HOSP 15MTG	HOSP EEM + 15MTG	44.35	6,953	12,602	98	38	228.5	613.0	77.6	1.8
HOSP 15 MTG AC	HOSP EEM + 15 MTG+AC	39.94	6,142	8,161	98	79	32.2	614.5	91.0	1.9
COLL MTG	COLL EEM + MTG	9.56	1,669	7,684	100	24	432.6	44.7	5.5	2.4
SOB PV	SOB_EEM + 1PV	1.09	199	1,110	49	—	201.7	1.46	—	25
SOB BO	SOB_EEM in Boston (MA)	1.45	265	1,399	—	—	41.85	8.87	—	—
SOB MTG BO	SOB_EEM+1 MTG in Boston (MA)	1.63	273	928	32	5	26.9	36.2	1.7	—
SOB MTG AC BO	SOB_EEM+1 MTG+AC in Boston (MA)	1.81	306	1,007	32	90	21.5	20.4	6.8	—

The cost savings of the integration of one or more HTFC into a hospital, a college, and a medium office building in LA area in comparison with the corresponding base cases with EEM included are presented in Figure 7. For the hospital, four 250 kW HTFC are needed in order to cover the base electric load whereas for the college and the medium office templates just one HTFC significantly exceeds their 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 in hospital savings of more than $860,000 in annual energy costs (O&M costs for the four HTFC included). Savings for the college and the medium office templates reach $120,000 and $114,000, respectively.

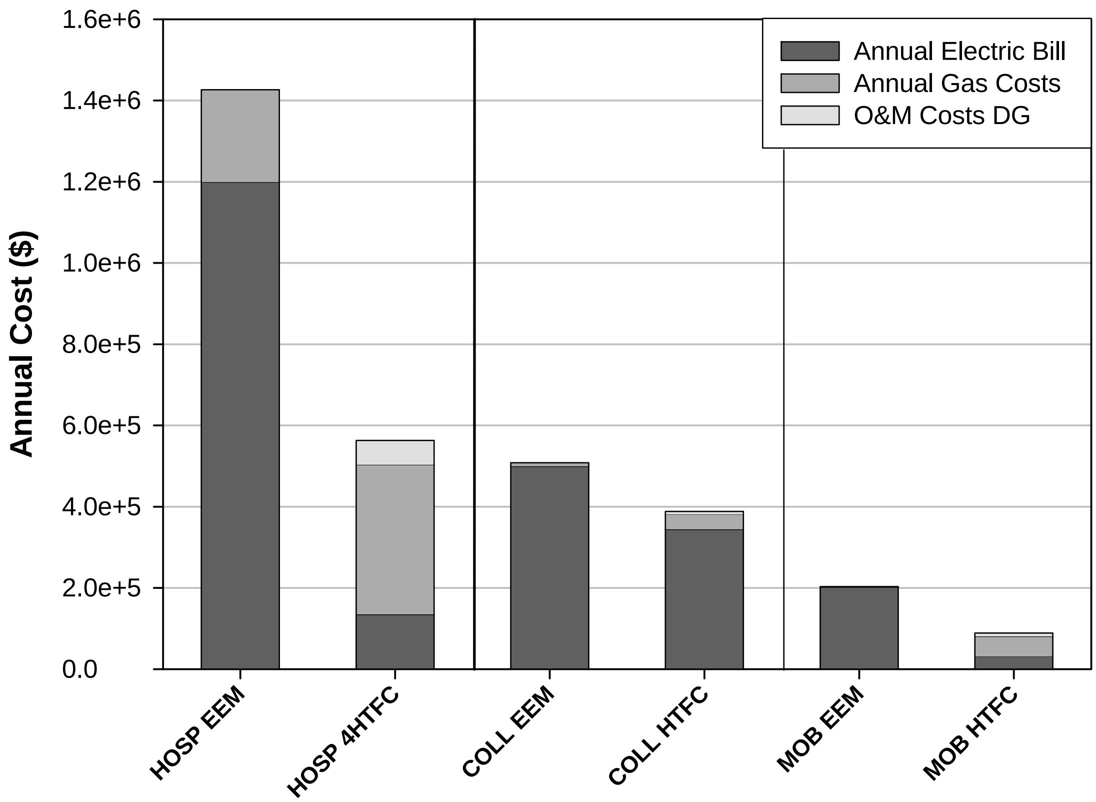


Figure 7: Annual electric, natural gas, and DG operating and maintenance costs for a hospital, a college, and a medium office with and without integrated high temperature fuel cells (HTFC).

The economics of the integration of MTG instead of HTFC is also studied for the four building templates considered, as shown in Figure 8. According to their base electric load, 1 60 kW MTG is adopted in the small office building and the college, 2 MTGs in the medium office building and 15 MTGs in the hospital. The economic annual savings in these cases are about: $12,000, $25,000, $41,000 and $507,000, respectively. Note that comparing the savings with the number of DG units installed, it becomes apparent that cost reductions are not just proportional to the number of DG units, but take into account may other parameters such as the DG annual operating schedule, the electricity and natural gas rate structures, and the amount of waste heat recovered.

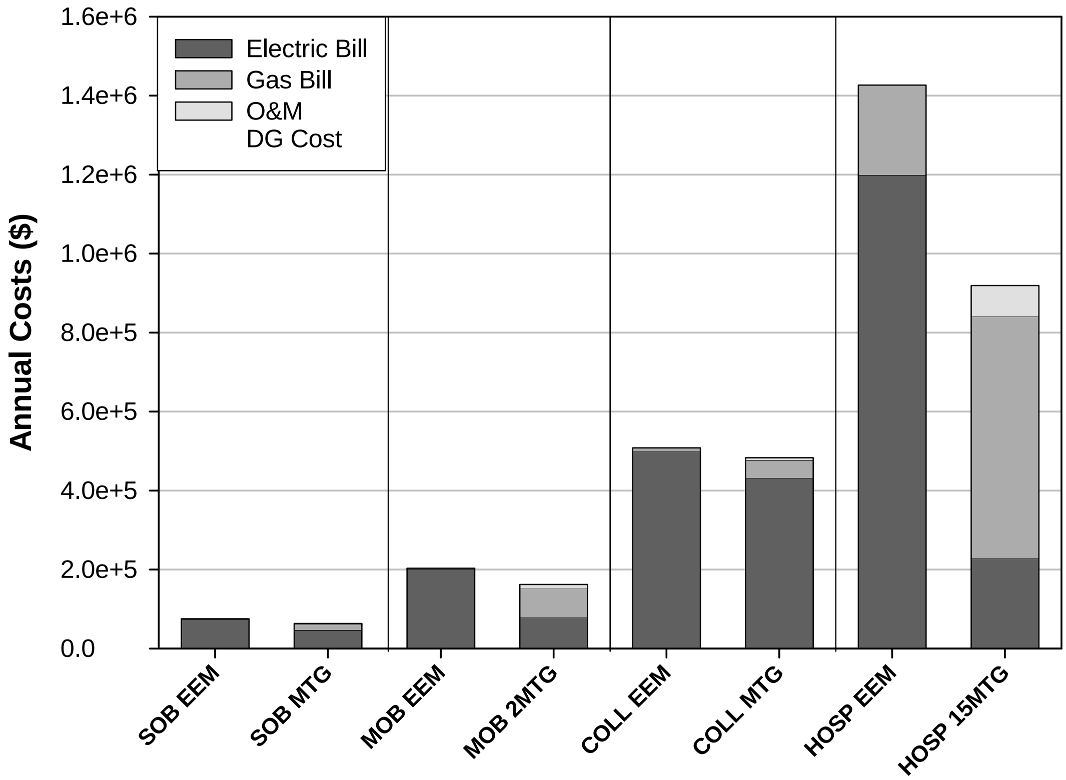


Figure 8: Annual electric, natural gas, and DG operating and maintenance cost for a hospital, a college, a medium office, and a small office with and without integrated micro turbine generator (MTG).

Comparing the annual saving of all the cases with MTG and with HTFC on the same power output basis, as shown in Figure 9, 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 MTG. As expected due their intrinsic higher electrical efficiency, HTFC integration provides, in general, more savings per kW than their corresponding MTG cases. However, as Table 9 shows, payback periods of MTG are usually shorter (1.8-5 years) than the ones of HTFC (3.5-6.6 years) due to the much lower capital costs of MTG.

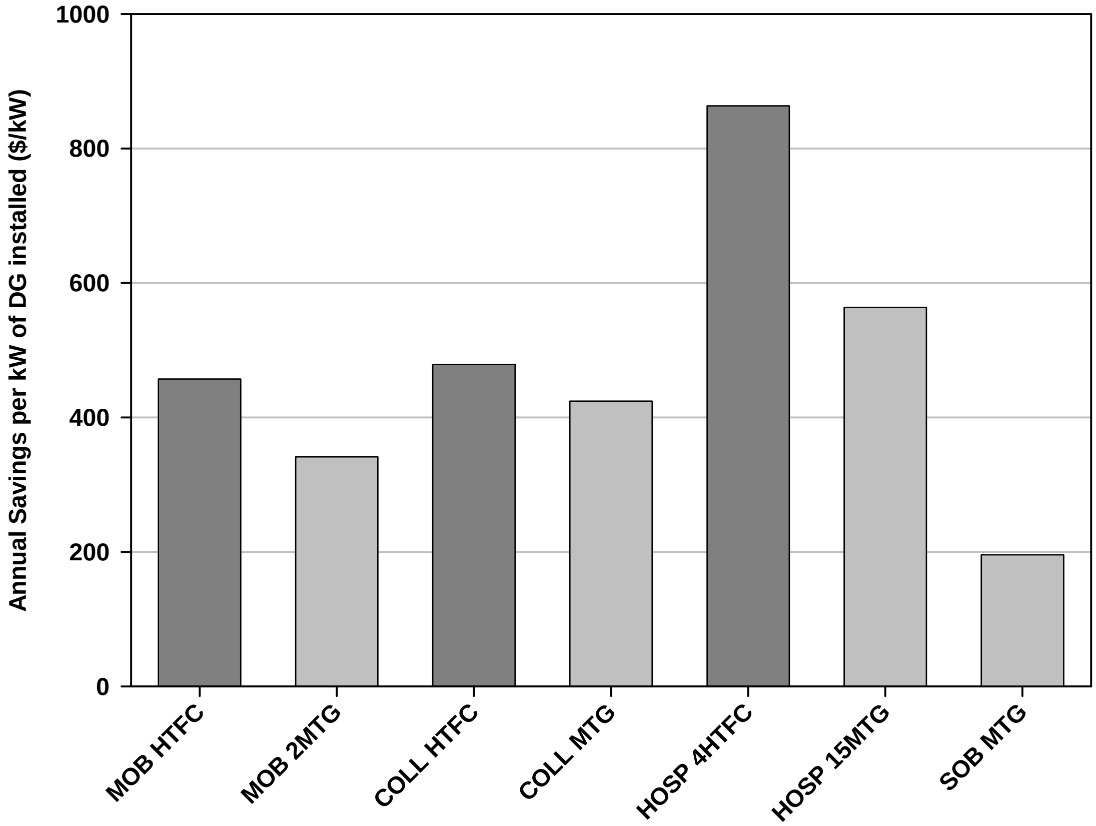


Figure 9: Annual savings per kW of DG power installed for various cases of DG-CHP integrated commercial buildings.

Although the integration of a 60 kW multi crystalline PV array into a small office building (Table 9) presents important annual reductions of 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 HTFC and MTG in the hospital building is, in both cases, more cost-effective than in the other buildings for 2 main reasons. First, the capacity factor of the DG units in the hospital is close to 100% because of the previously mentioned 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 (Figure 10), improving the overall efficiency of the system. The DG heat recovery utilization factor (ratio of available heat to used heat) is about 85% for the hospital with the four HTFC and goes down to 37% with the same building and 15 MTG. The assumptions of the model make only possible to use the waste heat for the space heating water loop in the hospital. Thus, the considerable amount of natural gas needed in the 2 hospital cases is not primarily due to the eventual temporal mismatch between waste heat available and space heating load, but mainly because a second domestic water loop exists in the building 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, replacing almost completely the natural gas demand. The two DG-CHP 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 those DG integrated cases show the least annual economic savings per unit of installed DG power (Figure 9).

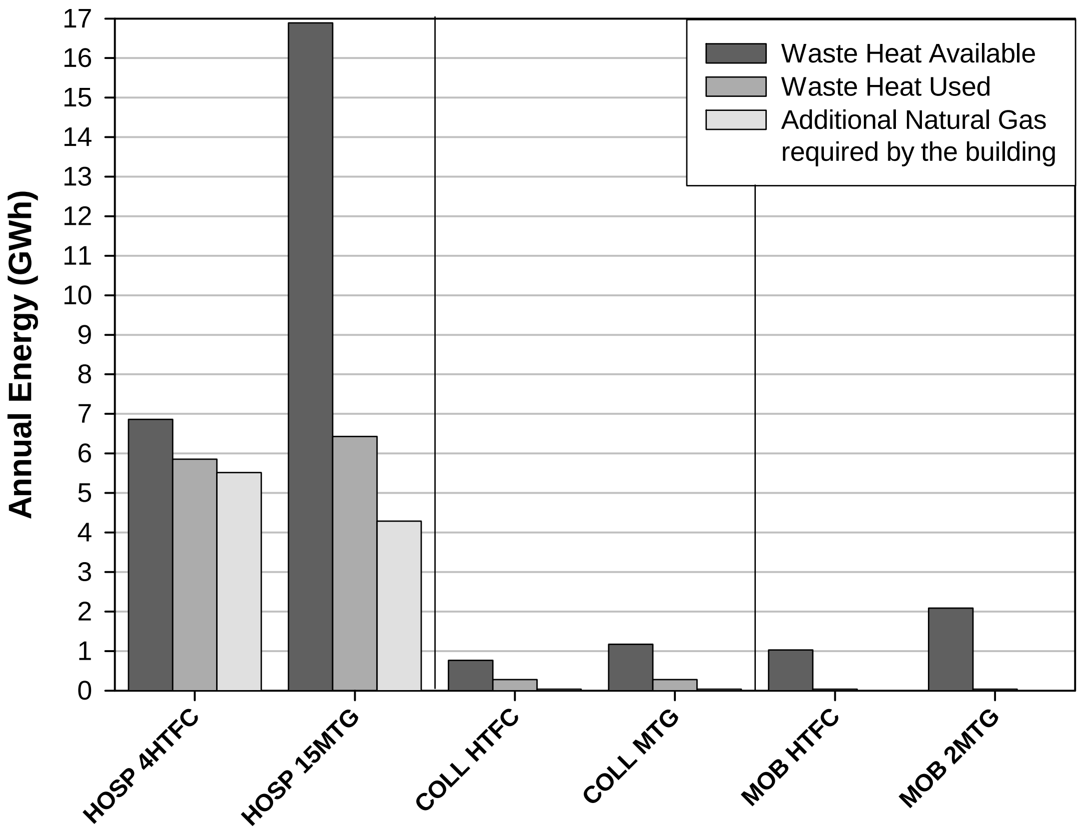


Figure 10: Waste heat available, waste heat used and additional natural gas required for the building, for various cases of DG-CHP integrated commercial buildings.

Figure 11 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 of the thermal loads of the building due to the introduction of thermally activated cooling provides a general boost of the DG heat recovery factor. The medium office template increases the waste heat used from 2% to 30% in the case of 2 MTGs, and from 3% to 47% in the case of 1 HTFC. Still, most of the waste heat available is lost because the relative 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 his heat recovery factor from 37% to 97% when cooling loads are thermally driven instead of power-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 and cooling load profiles are almost coincident and most of the waste heat is utilized. Regarding the hospital with 15 MTG, it was previously pointed out that summer E/T ratios of this building (about 1) 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 MTG is still more pronounced. Those reasons explain the rather low yearly averaged heat recovery utilization 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 there is a small demand of cooling and practically the same amount of waste heat, make that more than 20% of the available heat be wasted.

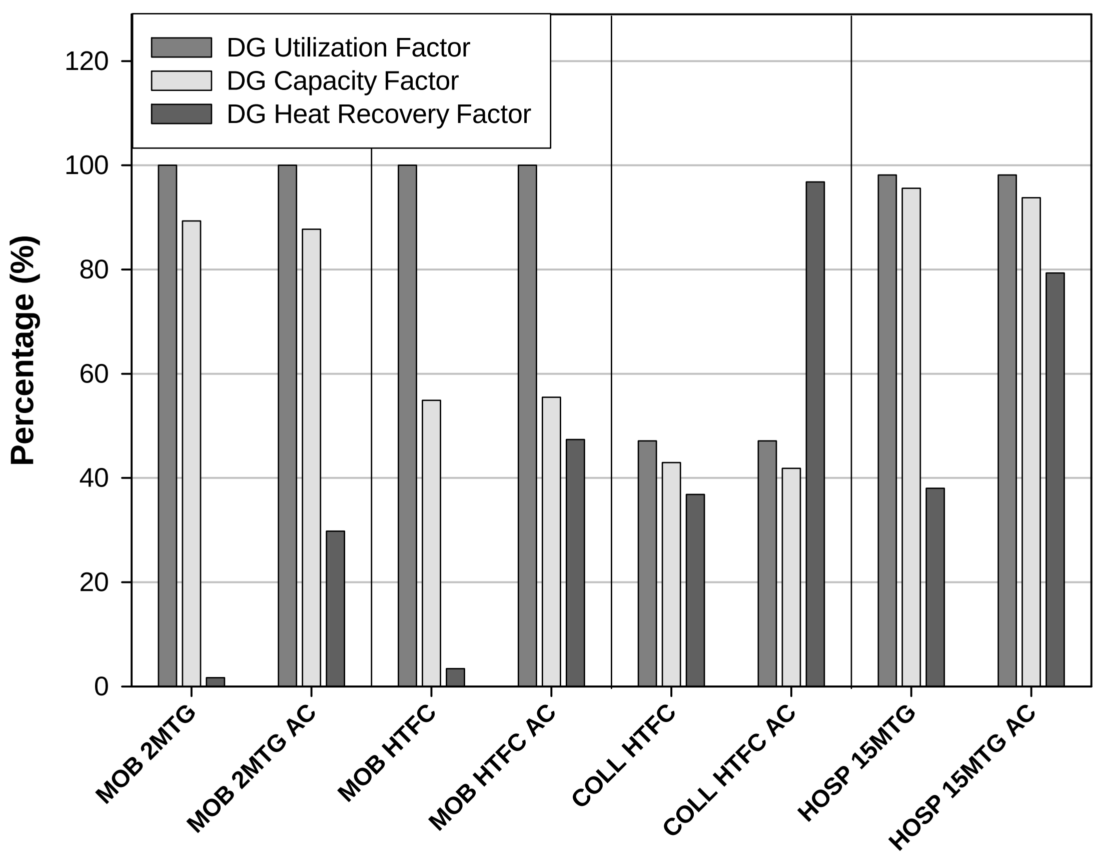


Figure 11: DG utilization factors, capacity factors, and heat recover factors for various cases of DG-CHP commercial building with and without integrated absorption cooling (AC).

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 cost for the absorption chiller are included, as shown in last column of Table 9. 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 utilized practically balance off the absorption chiller investment cost (1.8 years vs. 1.9 years).

1.6.11 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 the specific weather conditions and the 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 Boston area (MA). The main output results for those simulations are presented in the last 3 rows of Table 9.

Figure 12 compares the monthly electric and natural gas consumption and 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 LA, especially in winter months. Due to the harsher weather conditions in Boston, thermal loads for space heating in wintertime are considerably higher in Boston than in LA, whereas the domestic hot water demands are very similar. Thus, gas loads in winter months are about 10 to 20 times higher. From May to 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 expensive than in LA. The reason for that is that electricity grid prices in Boston are about 40% lower than in LA. The almost 100% higher natural gas rates in Boston only partially compensates for the above-mentioned difference in electricity prices because natural gas consumption in this small office template is relatively small. 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 any more, although environmental benefits of this integration in terms of reductions of primary energy consumption and NO_x emissions do still apply.

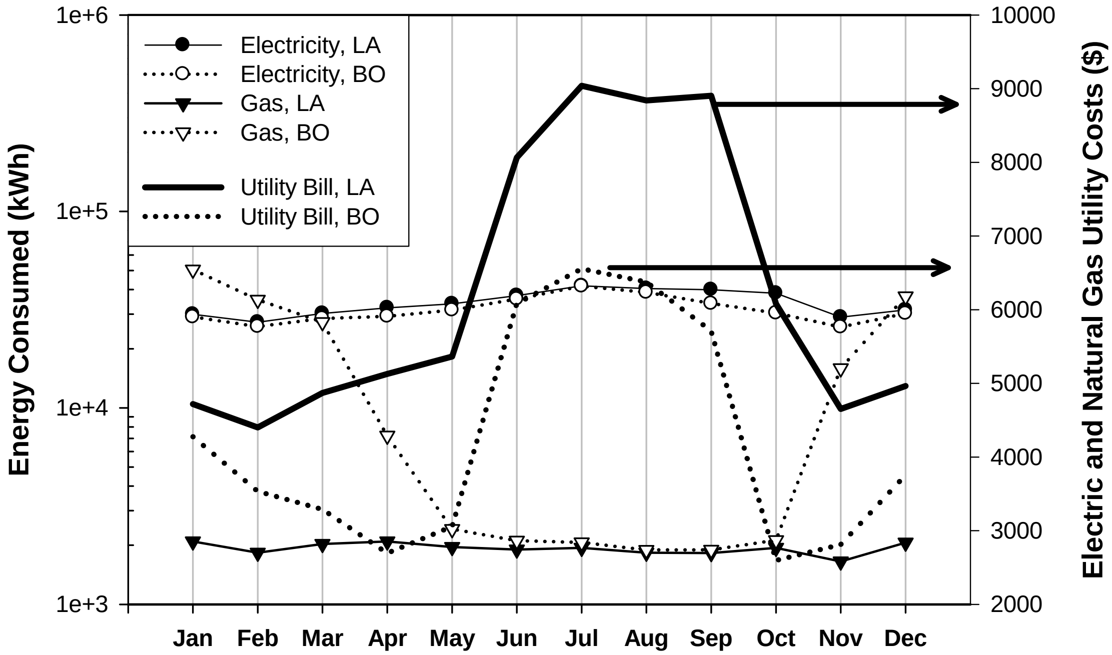


Figure 12: Comparison of monthly electricity and natural gas consumptions, and monthly utility bills for the same small office building located in Los Angeles area (CA) and Boston area (MA).

1.7 Economic calculator for fuel cells in southern California

As we have demonstrated in the thorough building integration analysis discussed in the previous point, DG economics is a complex function that involves several parameters such as the building energy profiles, the operation control DG strategy, the specific DG used, and the applicable rate structures for both natural gas and electricity supply.

For an optimal case in which the fuel cell is running at full capacity to meet the base load demand of a large institutional or commercial building, we have developed a simplified economic tool to assess annual savings with an optimized fuel cell operation. The economic tool is developed in an Excel spreadsheet form and includes commercial electric utilities rates of Southern California Edison (SCE), the Los Angeles Department of Water and Power (LADWP), and Riverside's public utility.

The inputs of this economic model are:

- Natural gas price ($/MMBtu)
- Fuel cell performance parameters
- Amount of waste heat recovered
- Month of the year

And the outputs of the model are:

- Decision for best fuel cell operation at full capacity (base loaded, peak mode, or peak and mid peak mode) on a basis of monthly savings.
- Monthly savings in the optimized operation mode.

This simplified tool was applied for a particular case of a HTFC with the same performance and economic parameters used in the previous section. All the fuel cell parameters and assumptions made are summarized below:

- Total output: 250 kW.
- Operating and maintenance costs: 0.007 $/kWh.
- Electrical efficiency (LHV): 47%.
- Thermal efficiency: 28%.
- Same nominal power output and efficiency throughout the whole year.
- Efficiency of displaced boiler: 80%
- Southern California Edison commercial rate TOU-8

Figure 13 presents annual savings of the building for the HTFC integration case as a function of natural gas prices. Two series, with and without waste heat recovery are included. Note how results of about $200,000 annual savings for a natural gas price of $0.4/therm are in good agreement with the hospital template with four HTFCs (HOSP 4HTFC) presented in the previous section. For the latter, the annual average natural gas rate is 0.46 $/therm, the HTFC capacity factor is 97% and the heat recovery factor 85%. Although these conditions should lead in principle to smaller savings than the ideal case with 100% capacity factor and heat recovery factor, slightly higher savings are obtained (about $215,000) because standby charges are not included in eQUEST economic calculations. For the rest of the HTFC integration cases presented in previous section (see Figure 9) annual savings are much smaller due to the lower capacity factors that are forced by the building energy profiles and the lack of net metering options in California.

This economic tool can be readily modified to analyze the optimized operation of a micro turbine generator or other types of fuel cells. To do so, the appropriate input values for the DG performance and costs are to be provided in the spreadsheet.

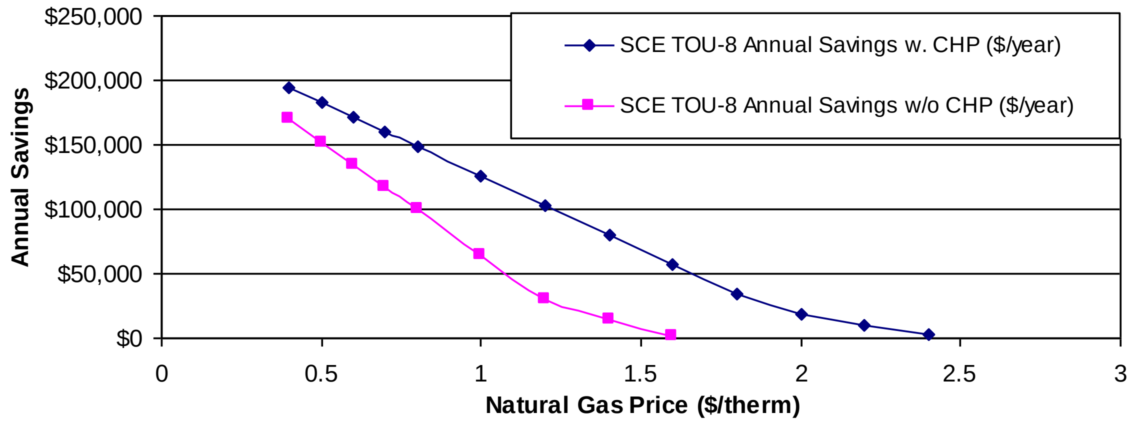


Figure 13: Comparison of annual savings vs. natural gas prices for a high temperature fuel cell of 250 kW with and without heat recovery.

It is important to note that the above figure integrates the various operating possibilities into a single optimal use curve. For that reason, there is a change in the slope of the curve that appears when the continuous operation the fuel cell shifts to peak operation for optimized savings. Note also how the combined heat and power device provides a significant improvement in the overall economics both in terms of the dollar amount saved and the range over which the savings occur.

1.8 Added value of advanced DG systems

In the previous sections we have presented the traditional financial case to analyze DG economics on the basis of strict energy cost savings. Under this traditional approach, only the most favorable cases of advanced DG integration into the built environment can compete with the business-as-usual case due to the necessarily higher capital costs of new technologies.

Nonetheless, these advanced DG solutions do provide a wide variety of value-added benefits to the different stakeholders and to society in general. Those benefits are difficult to translate into a monetized values and, therefore, cannot be used by DG advocates to further justify the economic feasibility of DG projects. A non-comprehensive list of those value-added benefits is presented below [13], [14]:

- Environmental:
    - Reduction of climate gas emissions and primary energy demand through renewable PV, through high electrical efficiency (fuel cells) or through high overall efficiency (both fuel cells and MTGs with CHP).
    - Low criteria pollutant emissions: PV and fuel cells with hydrogen have zero pollutant emissions, and fuel cells and MTGs with other fuels present also very low emissions in comparison with the average US grid.
    - Reduction in noise and vibrations (PV and fuel cells)

  - Lower transmission and distribution losses associated with the current paradigm of centralized power plants.
- Energy economic
  - Greater power quality and reliability due to the improved power electronics of the new DG technologies. Premium power users such as internet server farms and computerized banking systems are willing to pay more money to avoid a power interruption that could cost them millions of dollars for only a 1-hour interruption.
  - Less vulnerability to grid system attacks.
  - Decreased exposure to electricity price volatility.
  - Modularity of the DG systems (reduced forecasting risks, reduced financial risks, and reduced risk of technological or regulatory obsolescence)

Further research is required to quantify all the above value-added benefits of advanced distributed stationary power. Only when these additional benefits are introduced in the economic case will DG systems have a fair comparison with traditional systems. The authors recommend the implementation of new policies in the State of California to quantitatively account for the added values provided by advanced DG systems and promote in that way the early deployment of such systems. State buildings should be the first to adopt these technologies to demonstrate California's leadership and accelerate commercial deployment.

5. REFERENCES

[1] CSFCC, 2003, "White Paper Summary of Interviews with Stationary Fuel Cell Manufacturers, Draft 3.1.", California Stationary Fuel Cell Collaborative. pp. 10.

[2] Rabl, A. and P. Fusaro, *Economic and Financial Aspects of Distributed Generation*, in *Distributed Generation: The Power Paradigm for the New Millennium*. 2001, CRC Press LLC.

[3] EDR, 2001, "Design Brief: Options and Opportunities.", Energy Design Resources.

[4] Onsite, 2000, "The market and Technical Potential for Combined Heat and Power in the Commercial/Institutional Sector.", Onsite Sycom Energy Corporation, prepared for the U.S. Department of Energy.

[5] DOE, 2002, "Integrated Energy Systems (IES) for Buildings: A Market Assessment.", Resource Dynamics Corporation, prepared for the US Department of Energy. Contract No. DE-AC05-00OR22725

[6] EIA, 2000, "A Look at Building Activities in the 1999 Commercial Buildings Energy Consumption Survey (CBECS).", Energy Information Agency.

[7] CEC, 1999, "Market Assessment of CHP in the State of California.", Onsite Sycom Energy Corporation, prepared for California Energy Commission.

[8] McDonell, V.G., R.L. Hack, S.W. Lee, J.L. Mauzey, J.S. Wojciechowski, and G.S. Samuelsen. "Experiences with Microturbine generators systems installed in the South Coast Air Quality Management District," in TURBOEXPO 2003-Land, Sea, and Air, 49th ASME International Gas Turbine & Aeroengine Technical Congress. 2003. Atlanta, Georgia, US.

[9] EDR, 1998, "Design Brief: Integrated Energy Design", Energy Design Resources.

[10] EPA, 2001, "Environmental Technology Verification Report: Mariah Energy Corporation Heat PlusPower System.", Greenhouse Gas Technology Center, Southern Research Institute, prepared for the U.S. Environmental Protection Agency. SRI/USEPA-GHG-VR-13
[11] Bailey, O., B. Ouaglal, E. Bartholomew, C. Marnay, and N. Bourassa, 2002, "An Engineering-Economic Analysis of Combined Heat and Power Technologies in a microGrid Application.", Lawrence Berkeley National Laboratory, prepared for United States Environmental Protection Agency: Berkeley. LBNL-50023
[12] Medrano, M., J. Brouwer, G.S. Samuelsen, M. Carreras, and D. Dabdub. "Urban Air Quality Impact of Distributed Generation," in TURBOEXPO 2003-Land, Sea, and Air, 49th ASME International Gas Turbine & Aeroengine Technical Congressr. 2003. Atlanta, Georgia, USA.
[13] Peht, M. and S. Ramesohl, 2003, "Fuel cells for distributed power:benefits, barriers and perspectives.", Fuel Cell Europe, WWF.
[14] Little, A., 1999, "Distributed Generation: Understanding the Economics.", Arthur D. Little, Inc.