COOLING, HEATING, AND POWER (CHP) FOR COMMERCIAL BUILDINGS BENEFITS ANALYSIS

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ABSTRACT

We performed a detailed analysis of the energy consumption and end-user economics combined heat and power (CHP) systems in large-commercial buildings that included:

- Five generation technologies (standard and advanced microturbines, standard and advanced internal combustion (IC) engines, and high-temperature PEM fuel cells);
- Three building types (hospital, large office, and large hotel);
- Five US cities (New York, Los Angeles, Chicago, Miami, and Phoenix); and
- Utilizing recovered heat for both heating and absorption cooling.

Our detailed, hour-by-hour analysis includes a novel operating algorithm that makes the generate-versus-buy decision based on minimizing overall operating costs, including accounting for the impacts of electric demand charges.

Our analysis did not consider benefits beyond end-user energy-cost savings, such as improved power quality/reliability, transmission and distribution system (T&D) support, and possibly emissions credits. This is an important limitation as these other benefits can be significant.

Key findings include:

- High electric generation efficiency is of primary importance for CHP systems in typical commercial building applications. The increased production of heat from less-efficient generation technologies cannot compensate for their reduced electric output.

- CHP offers greater energy primary energy savings relative to distributed generation (DG, i.e., power only). For example, for a large office building in New York using an advanced engine generator, CHP increases energy savings from 21 percent to 31 percent.

- CHP generally offers payback periods similar to those for DG. Therefore, CHP will generally be economically attractive wherever DG falls within acceptable payback-period thresholds. Payback periods for CHP were generally 1 to 2 years in Los Angeles, 2 to 3 years in New York, 5 to 7 years in Chicago, and over 15 years in Miami and Phoenix.

While CHP systems in commercial buildings can provide attractive end-user energy economics in high-utility-rate areas, broad market penetration will depend on the extent to which evolving CHP business models can combine other benefits (power quality/reliability, T&D system support, and possibly emissions credits) with end-user energy-cost savings as the basis for making installation decisions. However, the value of these other benefits can be very difficult to quantify. In support of evaluating CHP business models, better and more quantified estimates are needed of the value of these other benefits.

INTRODUCTION

Combined heat and power (CHP) provides significant opportunities for energy and energy cost savings, as well as improved power quality and reliability, and transmission and distribution System (T&D) support. In industrial applications, energy and energy cost savings are generally increased significantly by recovering and utilizing the heat produced as a by-product of electricity generation. This, however, is not necessarily the case for many commercial buildings. Office buildings and retail stores represent the bulk of the commercial building floor space. In these building types, heating loads (primarily space heating and service water heating) are generally modest because:

- The need for service water heating is primarily limited to hand washing; and
- Space-heating loads, even in northern climates, are significantly

offset by two factors:

— Internal heat loads, associated with occupants, computers, printers, servers, fax machines, copiers, and other office equipment; and
— Much of the floor space, especially in large buildings, is not adjacent to external building surfaces, and, hence, is not rapidly cooled by the ambient (outside) temperature.

To more fully utilize the recoverable heat produced, thermally activated cooling equipment (such as absorption equipment and desiccant systems) can be used to serve space-cooling loads. We performed an analysis of CHP systems for a limited selection of commercial building applications to provide a better understanding of the energy consumption impacts and end-user economics of CHP systems. We did not, however, consider other benefits of CHP systems such as improved power quality and reliability, T&D system support, and possible emissions credits. This is an important limitation because these other benefits can be significant.

There are few detailed studies available that evaluate the energy impacts and economics of CHP systems in commercial buildings. Our analysis accounts for a) the variability in building electric and thermal loads, and b) key features of utility rates, such as demand and time-of-day charges. We employed detailed analyses (requiring a detailed computer model that accounts for hourly variations in building loads and utility rates) to accomplish this.

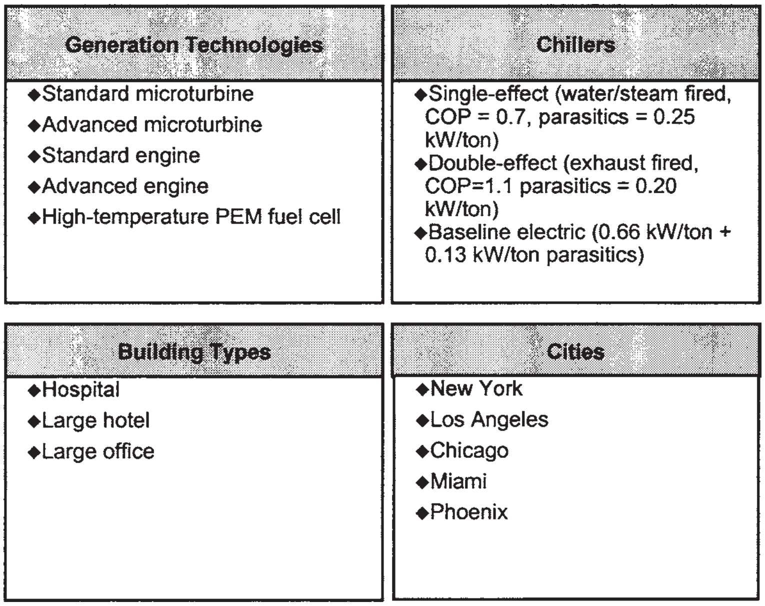
We generally report technical performance in terms of percent primary energy savings(1) achieved relative to a conventional building (without DG or CHP). The percentage is calculated by comparing the total primary energy used with the CHP system to that used by the conventional building. Some analysts report a combined efficiency, or energy utilization efficiency, for CHP systems. The combined efficiency is the combined electric energy and thermal load served by the CHP system, divided by fuel input(2). However, we believe that combined efficiency can be very misleading, so we avoid its use. The electric grid provides electricity at an average efficiency of about 35 percent (LHV)(3). On the other hand, conventional fuel-fired heating equipment provides heat at a typical efficiency of 90 percent (LHV)(4). Therefore, it can be difficult to judge whether a combined efficiency for a CHP system is higher than that for conventional equipment without calculating a weighted-average efficiency for conventional equipment providing the same electric and heating loads.

SYSTEM CONFIGURATIONS FOR ANALYSIS

Figure 1 outlines the matrix of generation technologies, thermally activated cooling equipment, building types, and cities considered. These variables are discussed below, along with the "baseline" (i.e., conventional) equipment characteristics assumed. We did not analyze CHP systems having either electric or thermal storage systems. Storage systems add cost and complexity, but may provide significant energy and operating-cost benefits. Furthermore, we did not consider strategies that shift discretionary loads to maximize the energy utilization of CHP systems.

Generation Technologies

We evaluated five generation technologies (see Table 1). We projected cost and performance characteristics for each technology for the



Generation Technologies

- Standard microturbine
- Advanced microturbine
- Standard engine
- Advanced engine
- High-temperature PEM fuel cell

Chillers

- Single-effect (water/steam fired, COP = 0.7, parasitics = 0.25 kW/ton)
- Double-effect (exhaust fired, COP=1.1 parasitics = 0.20 kW/ton)
- Baseline electric (0.66 kW/ton + 0.13 kW/ton parasitics)

Building Types

- Hospital
- Large hotel
- Large office

Cities

- New York
- Los Angeles
- Chicago
- Miami
- Phoenix

Figure 1. CHP benefits analysis system selection.

year 2005 (or after), and for production volumes of 10,000 units/year. This production volume is much higher than current production volumes for microturbines and, therefore, our installed-cost projections for microturbines are below current costs.

We use the term "standard" technology (for example, standard microturbine) to refer to a technology having performance characteristics typical of the products on the market today. We use the term "advanced" technology to refer to a technology that is further developed relative to the "standard" technology. Although we do not specifically designate it as advanced, the high-temperature proton-exchange-membrane (HTPEM) fuel cell is most definitely an advanced technology. In fact, no such technology is in the market place today (to which we could refer as "standard")(5). Our cost and performance projections for advanced technologies assume that ongoing research and development efforts will achieve their cost and performance goals. In particular, the HTPEM cost and performance pro-

Table 1. Generation technologies summary[a].

Generation Technology	Installed Cost ($/kW)	Non-fuel O&M Cost ($/kWh)	Nominal Electric Generation Efficiency (%LHV)[b]
Standard Microturbine	$880	$0.015	26%
Advanced Microturbine	$880	$0.015	31%
Standard Engine	$570	$0.010	35%
Advanced Engine	$710	$0.012	42%
High-temperature Proton-exchange-membrane (HTPEM) Fuel Cell[c]	$1200	$0.015	40%
Grid Electric Baseline	*$0*	*$0*	*35%*[d]

a) Cost and performance characteristics projected for 2005 and for production volumes of 10,000 units/year, unless noted otherwise.

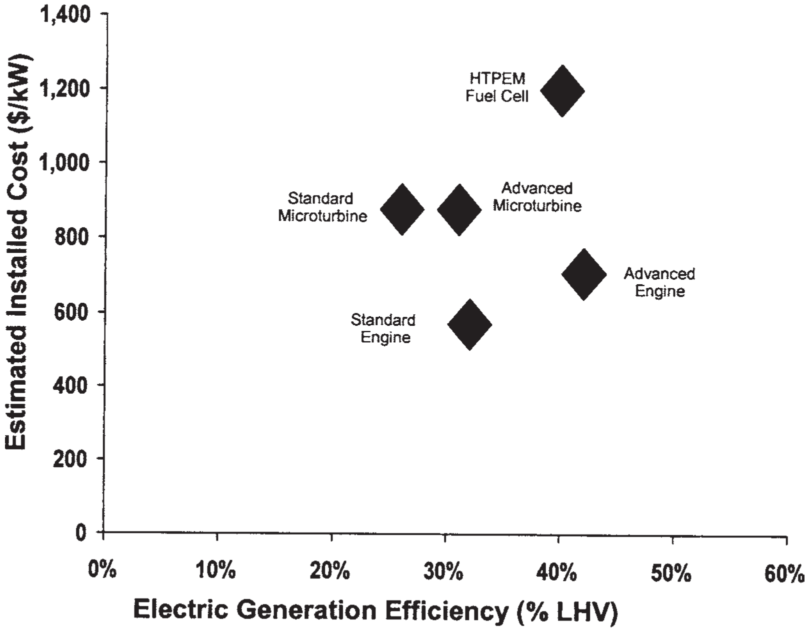
b) Includes power-conditioning equipment and/or electric-generator efficiencies, as appropriate.

c) We analyzed high-temperature PEM because the temperature of the heat available from low-temperature (conventional) PEM is too low for practical use in most commercial building heating applications.

d) For year 2005, HHV value of 31.8 percent [1] converted to LHV assuming that the weighted average of HHV to- LHV ratios for the mix of fuels used in generating grid-supplied electricity is the same as the ratio for natural gas.

jections are the most speculative among the generation technologies. Realistically, the time horizon for achieving the cost and performance projections for HTPEM will probably be well beyond 2005.

Figure 2 shows generator technology cost as a function of generation efficiency. As evident from the figure, the engines have much lower cost-to-efficiency ratios relative to microturbines or fuel cells. This does not mean, however, that engines will always be the preferred choice for CHP systems. Engines may have disadvantages relative to the other technologies, such as more noise and vibration, higher weight, higher emissions, and more frequent maintenance requirements. Our analysis attempts to account for only some of these factors (such as weight and vibration, to the extent that they impact installation costs, and more frequent maintenance, to the extent that it impacts non-fuel O&M costs).



Microturbine and fuel cell costs are based on 10,000 units/yr. production with 40% mark-up over manufacturer's cost, and 50% installation costs. Advanced engine costs are based on Y2010 industry goals for natural gas compression-ignition engines. Standard engine costs are based on current retail cost projections for beyond Y2005.

Figure 2. Generation-technology cost versus efficiency.

Building Types

We selected hospitals, large hotels, and large office buildings for analysis. We focused on larger commercial buildings because we judged them to be more likely candidates for CHP systems. For our detailed analysis, we required hourly load data for prototypical buildings. Table 2 summarizes the characteristics of the prototypical buildings selected. The characteristics of each building type vary depending on the city, reflecting the regional variations in typical construction characteristics. In some cases, the variations are substantial. For example, a prototypical large office in New York is 419,000 square feet, while a prototypical large office in Phoenix is only 142,000 square feet. To better focus on energy impacts associated with climate and utility rates, we report energy impacts per square foot of floor area (commonly referred to as energy intensities). However, the building types will also vary from city to city in a) type and number of windows, b) wall, floor, and roof insulation, and c) other construction characteristics – all of which will impact building loads independent of climate.

Baseline Building Characteristics

Analysis of a building using CHP only has relevance if compared to a baseline building against which energy consumption and cost comparisons can be made. Because the vast majority of commercial buildings purchase all electricity consumed from the electric grid, grid-purchased electricity is the logical source of electricity for the baseline building. The national average generation, transmission, and distribution efficiency is roughly 35 percent on a LHV basis (see Table 1). We did not account for variations in the efficiency of grid-supplied electricity associated with various utility service areas, building location within the grid, temperature and weather conditions, overall demand on the grid, or other factors.

Because the waste heat recovered and utilized will displace thermal loads normally supplied by other means, it is also important to define the baseline equipment used to supply thermal loads, including service-water heating, space heating, and space cooling. There are two general categories of space-conditioning equipment used in commercial buildings:

- Light Commercial: Packaged unitary equipment (rooftop equipment); and
- Large Commercial: Engineered systems (chillers and boilers).

Table 2. Prototypical commercial building characteristics.

Building Type[a]	City	Floor Area (ft^2)	Coil[b] Heating: Peak (MMBtu/hr)/ Annual (MMBtu/yr)	Coil[b] Cooling: Peak (MMBtu/hr)/ Annual (MMBtu/yr)	Non-coil[c] Electric: Peak (MW) Annual (MWh/yr)
Hospital	New York	386,000	10.5/16,000	8.4/22,000	1.4/9,000
	Chicago	364,000	13.0/7,000	8.5/20,000	1.3/8,500
	Miami	315,000	4.2/1,200	6.5/55,000	1.1/7,300
	L.A.	250,000	2.3/1,100	6.8/15,000	0.9/5,700
	Phoenix	254,000	4.2/1,300	8.3/30,000	0.9/6,000
Hotel	New York	494,000	15.5/6,300	9.6/18,000	1.4/6,300
	Chicago	218,000	9.2/6,400	4.9/8,800	0.6/2,800
	Miamo	194,000	2.9/97	3.6/27,000	0.5/2,500
	L.A.	203,000	1.7/610	4.6/4,600	0.5/2,600
	Phoenix	178,000	3.3/580	5.3/16,000	0.5/2,300
Office	New York	419,000	5.9/4,600	5.8/7,400	1.3/4,900
	Chicago	352,000	5.4/3,500	5.7/7,000	1.1/4,200
	Miami	159,000	1.7/150	2.3/11,000	0.6/2,100
	L.A.	197,000	1.7/910	3.9/5,200	0.7/2,300
	Phoenix	142,000	1.8/760	3.5/7,600	0.5/1,800

a) Each building is current vintage, meaning that its envelope (wall and ceiling R-values, for example) complies with ASHRAE Standard 90.1 The heating set-point is fixed at 74°F and the cooling setpoint is fixed at 76°F at all hours.[2]

b) Coil loads are given as the thermal loads at the chiller or boiler and do not include hot water loads.

c) Non-coil electric loads include all electric loads including lighting, equipment, and HVAC parasitic loads (fans, etc.) but do not include loads from electric cooling or heating equipment.

Because the building types considered in this analysis typically use engineered systems, we used chillers and boilers for the baseline space-cooling and heating equipment. Because electric chillers dominate the chiller market(6), we used electric chillers as a baseline. We further assumed that the electric chillers are water-cooled because:

- The building types we analyzed often use water-cooled chillers; and
- The lithium-bromide absorption chiller(s) used with CHP systems to supply space-cooling loads will require cooling towers. If an end user did not consider water-cooled electric chillers, then they likely would not consider a CHP system incorporating absorption chillers.

The most common types of water-cooled electric chillers are reciprocating and centrifugal. Rather than double the size of the analysis matrix by considering both reciprocating and centrifugal chiller baselines, we simply averaged the efficiencies of the two chiller types, using efficiencies of best-available chillers, to form a hybrid baseline (see Table 3).

Table 3. Baseline electric chiller efficiency calculation.

Equipment Type	**Seasonal Performance, IPLV (kW/ton)**
Water-cooled, Reciprocating Chiller—Best Available	0.84[a]
Water-cooled, Centrifugal Chiller—Best Available	0.47[a]
Average Water-cooled Chiller	0.66
Cooling Tower[b]	0.13[a]
Average Used for Analysis (Chiller and Tower)	0.79

a) From [4].

b) Cooling-tower parasitics are included because they differ for electric and absorption chillers. Parasitics associated with the building distribution system are not included, because they will be the same for either chiller type.

We assumed that end users who install CHP systems will insist on having sufficient capacity in the baseline cooling system to meet the building's design cooling load because:

- In retrofit applications, the baseline chiller plant already exists, so it is too late to avoid the full capital investment; and
- In new construction or retrofit applications in which the baseline equipment requires replacement anyway, the end user may not wish to be obliged to operate the CHP system to meet peak cooling loads when operation for electric generation is not justified. Also, the end user may not feel that the reliability of the CHP system is sufficiently high to depend on it to meet peak cooling loads.

We assumed that the baseline building uses a natural-gas-fired boiler having an 81 percent (HHV) efficiency for space heating. We assumed that the service-water-heating equipment in the baseline building uses the same fuel, and has the same efficiency, as the space-heating equipment.

Therefore, our economic analysis includes no credit for reduced capital costs for the baseline cooling plant. However, there will be situations in which the CHP system installation coincides with chiller retrofit/replacement. In these cases, installing co-fired (fuel and/or waste heat) absorption chillers could displace part of the baseline electric plant.

The selection of baseline equipment can have a significant impact on the calculated economics and energy savings of CHP systems. For example, seasonal efficiencies of light-commercial equipment (often used in buildings of three stories or less) are typically 1.2 to 1.6 kW/ton for space cooling. For the purposes of this analysis, this equipment would consume over 50 percent more energy per unit of cooling delivered relative to the baseline equipment we used(7). If space heating in the baseline building is supplied by electric-resistance heating, the baseline equipment would consume about 2.5 times as much primary energy per unit of space heating delivered relative to the baseline we used. In fact, if the heat recovered is displacing electric-resistance heating, the utilized heat has as much value as the electricity generated by the CHP system(8).

Thermally Activated Cooling Equipment

Table 4 lists the waste-heat-fired, thermally activated cooling equipment evaluated in this analysis. For each generation technology, we selected an appropriate type of absorption chiller to operate off the waste heat. We did not evaluate desiccant dehumidification systems. Evaluation of CHP systems using desiccants should be the subject of future analyses.

Table 4. Cooling technologies summary.

Generation Technology	Cooling Technology	Installed Cost ($/Rated Ton)	Annual Non-fuel O&M Cost ($/Rated ton)	Minimum Activation Temperature	Chiller COP[a]	Cooling Tower Parasitics (kW/ton)	Combined Chiller and Tower COP
Standard and Advanced Engines HTPEM	Water/Steam-fired Single-effect Chiller	$500	$15	170°F	0.7	0.25	0.6[b]
Standard and Advanced Microturbines	Exhaust-Fired Double-effect Absorption Chiller[c]	$650	$20	340°F	1.1[d]	0.20	0.9[b]
—	*Displaced Electric*	*$300*[a]	*$25*[e]	—	*1.7*[f]	*0.13*	*1.4*[g]

a) Coefficient of Performance (Btu of cooling Output/Btus of Heat Input). Calculated based on higher-heating value (HHV) of fuel, consistent with conventional practice for cooling equipment.

b) Primary energy COP. Tower parasitics converted to primary energy based on 31.7 percent (HHV) efficiency of the electric generation, transmission, and distribution system (from Table 1).

c) Exhaust-fired, single-effect chillers can be used with microturbines, as is being demonstrated currently at the University of Maryland. Depending on the application, the sing-effect chiller may be more cost effective. However, the cooling load provided by either chiller would be similar, as the ability of the single-effect chiller to extract more heat from the exhaust gas is roughly balanced by the higher COP of the double-effect chiller.

d) Arguably a somewhat higher COP would be appropriate given that there are no burner inefficiencies with waste-heat recovery. However, the impacts on overall CHP system performance would be small.

e) For reference only. We assumed that there will be no savings in capital cost or non-fuel O&M cost for the electric chiller plant when a CHP system is used.

f) Primary energy COP corresponding to 0.66 kW/ton IPLV (from Table 3 and 31.7 percent (HHV) efficiency of the electric generation, transmission, and distribution system (from Table 1).

g) Primary energy COP corresponding to 0.79 kW/ton IPLV, including tower parasitics (from Table 3 and 31.8 percent (HHV) efficiency of the electric generation, transmission, and distribution system from Table 1).

Table 5 lists the cost and performance characteristics of the equipment used to recover heat for heating loads.

Table 5. Summary of heat-recovery heating equipment.

Heat Source	Heat-Recovery Equipment	Installed Cost ($MMBtuh)	O&M Costs ($MMBtuh)	Effectiveness	Pressure Drop (dP/P)[a]
Microturbine Exhaust HTPEM Tail Gas	Gas-to-water Heat Exchanger	$10,000	–$0	85%	2%
Engine Coolant Loop[c]	Coolant-to-water Heat Exchanger	$10,000	–$0	85%[b]	—[d]
Displaced Boiler	—	—	—	*81% (HHVB)*[e]	—

a) Pressure drop divided by absolute pressure at heat-exchanger inlet.
b) Heat loss to ambient is assumed negligible, so the heat-exchanger efficiency is 100 percent
c) Coolant recovers heat from both engine jacket and exhaust.
d) Additional coolant-pump parasitics associated with the heat exchanger are neglected.
e) This is actually an efficiency, not an effectiveness.

Cities and Utility Rates

Table 6 lists some of the climate characteristics of the five cities selected for analysis. The five cities provide a range of climate conditions. More importantly, they provide a range of utility rates and rate structures.

We used 2002 rate structures appropriate for the building types considered in our analysis. However, we did not account for the fact that incorporating CHP may change the rate structure applicable to the building, nor did we account for stand-by or other charges that may be imposed on CHP system users.

Table 6. U.S. Cities selected for analysis.

City	Latitude	1% Heating Design Dry-Bulb Temperature	1% Cooling Design Dry-Bulb Temperature	Coincident Humidity	DOE Climate Zone
Los Angeles	33.93N	45°F	81°F	39%	5
New York	40.65N	15°F	88°F	46°F	3
Chicago	41.98N	–1°F	88°F	50°F	2
Phoenix	33.43N	37°F	108°F	14%	4
Miami	25.82N	50°F	90°F	56%	5

APPROACH

We developed a detailed computer model to evaluate the energy savings and economics of CHP systems in selected commercial building applications. We discuss our approach to the analysis and our results below.

Key Assumptions

Table 7 lists the key assumptions used in our detailed computer model. The table divides the key assumptions into those tending to favor CHP systems and those tending to favor conventional grid power. In our judgment, the net impact of these assumptions generally favors CHP systems, but there certainly may be cases where this is not true.

Perhaps the most important assumptions tending to favor CHP systems are:

- Manufacturing economies of scale are achieved
- There is no degradation in generation efficiency when operating at part load
- Generation capacity can ramp up or ramp down as quickly as necessary to match building loads
- There are no stand-by charges or other utility-imposed charges for CHP

Table 7. Key assumptions used in detailed analysis.

Tending to Favor CHP	Tending to Favor Conventional Grid Power
• Did not consider utility stand-by charges. • Did not consider impacts of unscheduled outages. • No part-load efficiency degradation for generators or chillers. • No significant time required for ramp up or ramp down for generation capacity. • "Smart" control algorithm assumes perfect knowledge of future building loads and ambient temperatures. • Performance estimates for fuel cells, advanced engines, and advanced microturbines based on achieving R&D goals. • Manufacturing economics of scale are achieved. • Set 5-year allowable payback period. • Weekday rate structures are assumed to apply on weekends as well. • There are no penalties or restrictions for increased site emissions associated with CHP.	• Thermal and electric storage systems not considered. • Shifting of discretionary loads not considered. • Did not consider value of premium power (baseline would be conventional building with back-up generator or UPS in that case). • No rebates or incentives are available for use of CHP. • Did not use interruptible utility rates. • No net metering. • Cooling equipment installed for CHP system is in addition to conventional cooling plant. Did not consider co-fired absorption equipment. • Waste heat supplies cooling loads first, then heating loads, regardless of which provide greater economic value. • Model uses hourly averages, which tends to underestimate peak electric demand and hence, tends to underestimate demand charge savings. • Absorption chiller plant and heat-recovery heat exchanger are sized to utilize all heat available from the generator operating at full load. The economically optimized plant and heat exchanger would likely be smaller. • Desiccant systems not considered in this analysis but may improve economics in some applications.

- The impacts of unscheduled outages are not considered
- A five-year simple payback is acceptable.

Perhaps the most important assumptions tending to favor conventional grid power are:

- No value is assigned to premium power
- No net metering is allowed (i.e., no sale of excess electricity to the grid)
- Thermal and electric storage systems are not considered

- Strategies to shift discretionary loads are not considered.

Computer Model Structure

To perform a more refined analysis of CHP systems, we developed a detailed computer model using Microsoft® Visual Basic (Version 6.0) and an object-oriented programming strategy. The model uses an hour-by-hour simulation for one year of CHP-system operation, as outlined in Figure 3.

Equipment Cost and Performance Projections

We projected equipment cost and performance characteristics for 2005 (or later), based on annual production volumes of 10,000 units. In general, we based cost and performance projections on some combination of:

- Bottom-up analyses using detailed cost and/or performance models
- Top-down analyses based on current cost and performance characteristics, extrapolated to the appropriate production volumes and (for advanced generation technologies) targeted design enhancements
- Discussions with equipment manufacturers and distributors.

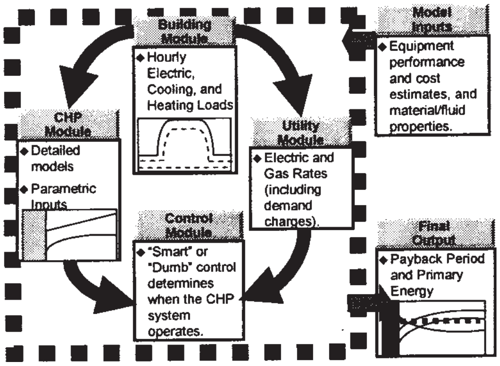


Figure 3. Overview of detailed computer model for CHP-system simulation.

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Operating Strategy and Associated Control Algorithm

We used a "smart" operating strategy that takes full advantage of the model's perfect knowledge of future building loads. In real life, one does not have perfect knowledge of future building loads, so any real-life operating strategy may not do quite as well as our model would suggest. It does, however, reasonably represent the best one can do.

We developed a control algorithm for the operating strategy. The control algorithm ensures that building loads (power, heating, and cooling) are always met. Loads are met through some combination of on-site-generated power, grid-purchased power, utilization of recoverable heat for cooling and/or heating, and use of conventional cooling and heating equipment for cooling and heating. The key decision made by the control algorithm is, for each hour of the simulated year, whether to operate the on-site generator and at what capacity to operate it (between 0 and 100 percent capacity) to minimize operating costs.

Recoverable heat from the generator is first utilized to satisfy cooling loads, and then (to the extent additional heat is available) to supply heating loads. No comparison is made of the "value" of supplying cooling loads versus heating loads.

An economically sound operating strategy will need to consider utility rate structures (primarily the electric rate structure) to deliver the most cost-effective service to the end user. In fact, utility rate structures can have a significant impact on the logic of the control algorithm for such an operating strategy. Accounting for the impacts of demand charges introduces a significant level of complexity because demand charges are not incurred on an hourly basis, but rather assessed at the end of the month, when all grid-electric-power draws are known. Our control algorithm uses detailed electric rate structures.

For a given CHP system capacity, the control algorithm determines the hourly operation of the CHP system that minimizes operating costs, accounting for electric and gas/fuel oil prices, and non-fuel O&M costs. The algorithm accounts for the offset in electricity and gas/fuel-oil consumption associated with utilizing recoverable heat. The algorithm does not directly consider primary energy savings or emissions reductions in determining whether to run the generator or purchase from the grid.

Utility Rates

Our model utilizes actual 2002 electric rate structures for each city analyzed. For each city, we selected the rate structure that, in our judgment, best applied to large offices, large hotels, and hospitals (the building types analyzed). We selected only one rate structure per city.

While our model of electric utility rates includes some simplifications, it captures the key features of most rate structures, including demand charges, energy charges, and time-of-day charges, all of which can be varied by month. For each month, the user can input up to 24 (one for each hour) electric demand charges, 24 electric energy charges, and 24 gas energy charges. The model does not include weekday/weekend pricing, time-of-day demand charges, or ratchet rates. Demand charges are calculated based on hour-long average power draws (because our model analyzes hour-long increments), even though in real life demand charges are generally assessed based on 15-minute intervals. This assumption will tend to underestimate demand charges. The model does not include real-time pricing rate structures, although this would be an interesting addition for future analysis. The model does not consider net metering (selling generated electricity to the grid) or stand-by charges (or other charges that utilities may impose on CHP system users). Net metering and/or stand-by charges can have significant impacts on the energy savings and economics of CHP. Figure 4 shows the average electric and gas rates for the buildings that we modeled.

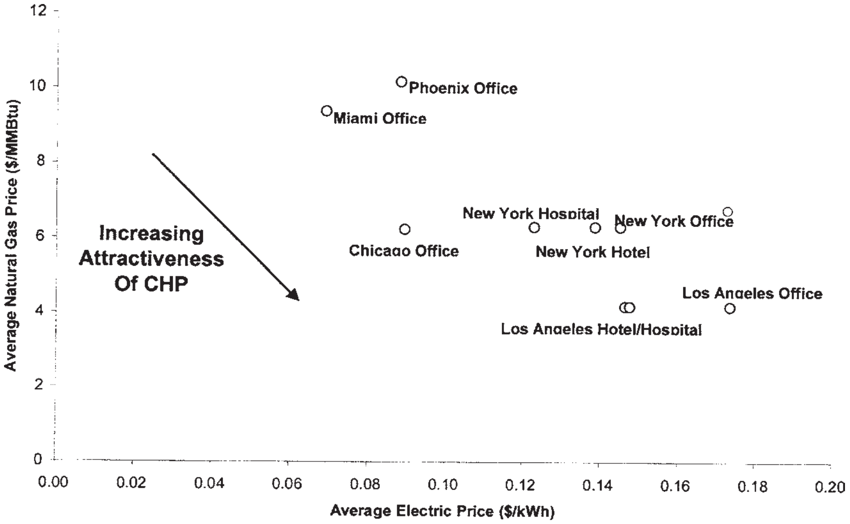


Figure 4. Average utility prices for the prototypical buildings modeled.

CHP System Sizing

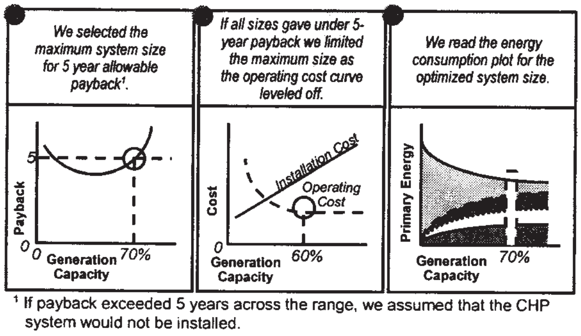
The operating strategy discussed previously minimizes operating costs once a CHP system has been selected and installed. However, we also need an approach to determining the most appropriate CHP system plant size for a particular application. We simulated CHP systems ranging in generation capacity from 0 percent (no CHP system) to 100 percent of the baseline building peak electric load(9) (using 10-percent increments). We did not independently vary the sizes of the absorption chiller plant and the heat-recovery heat exchanger. Rather, we simply sized the absorption chiller plant to be able to utilize the all of the waste heat available from the generator operating at full capacity. We sized the heat-recovery heat exchanger similarly. These simplifying sizing assumptions undoubtedly result in absorption chiller plants and heat-recovery heat exchangers that are larger (and more expensive) than is economically optimum. However, because the capital cost of the CHP system is dominated by the cost of the generator, the impacts of these sizing assumptions probably have only a modest negative impact on system economics and would not change any conclusions reached.

As discussed previously, we made several important assumptions about end-user economics:

- All end users are willing to accept up to a five-year simple payback period for a CHP system installation
- No rebates or other incentives (from government, manufacturers, utilities, or other parties) are considered(10)
- No economic value is placed on the benefits of improved power quality and reliability associated with the CHP system. In reality, these benefits would be of significant value to many end users(11)
- No stand-by charges or other penalties are imposed by the electric utility
- Net metering is not permitted
- End users place no value on reducing energy consumption (except to achieve cost savings)
- There will be no penalties or restrictions for increased site emissions (such as NO_x) associated with CHP-system operation.

We based our economic analysis on simple payback period because this metric is understood by a wide audience. However, we also recognize the limitations of simple payback(12), and sought to capture some of the realities associated with more sophisticated economic analysis techniques (such as net-present value or life-cycle cost analyses). However, we did not actually use these more sophisticated techniques.

We simulated the performance of CHP systems for a given building type and city over the full range of plausible generation capacities (from 0 to 100 percent of the baseline building peak electric load). We then plotted primary energy consumption intensity (consumption per square foot), installed cost, operating cost, and payback period as a function of system capacity. Finally, we used the method outlined in Figure 5 to select the economic optimum CHP-system size.



1 If payback exceeded 5 years across the range, we assumed that the CHP system would not be installed.

Figure 5. Summary of method to select CHP system size.

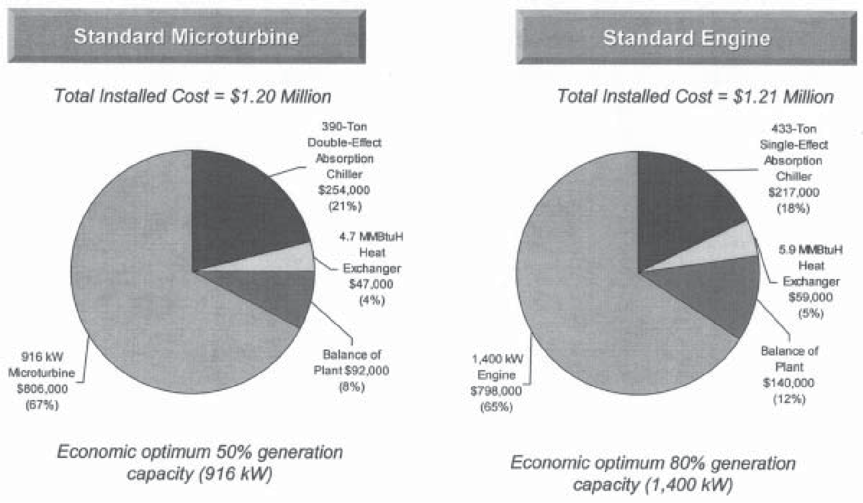


Figure 6. Equipment cost breakdown of CHP systems installed in a New York large office building.

RESULTS OF DETAILED ANALYSIS

Selected results of the detailed analysis are summarized below.

Primary Energy Consumption and End-User Economics

Figure 6 shows the breakdown of the equipment capital costs required to install a CHP system for a New York large office building and two generation technologies—standard microturbine and standard engine. Capital costs associated with the generation technology alone account for 60 to 70 percent of the CHP-system installed cost.

Figures 7 through 14 compare primary energy consumption intensities and simple payback periods, respectively, for logical groupings of the simulations completed. Energy consumption and payback are plotted as a function of generation capacity, up to 100 percent of the annual peak electric load for the baseline building. The economic optimum capacity is indicated on each curve. Observations drawn from each figure follow.

DG (Power Only) Vs. CHP – Standard Microturbine and Advanced Engine; New York Large Office Building (Figures 7 and 8):

- Heat recovery improves the primary energy impact associated with a standard microturbine CHP system from a modest increase (relative to the baseline building) to a modest savings.
- Heat recovery increases the primary energy savings associated with an advanced-engine generator CHP system from 21 percent to 31 percent at the economic optimum generation capacities.
- Heat recovery has little impact on payback for either the standard microturbine or the advanced engine.
- Paybacks are significantly better for the advanced engine (2 to 3 years) relative to the standard microturbine (4 to 5 years).

CHP Systems with Various Generation Technologies in New York Large Office Building (Figures 9 and 10):

- Primary energy savings at the economic-optimum capacities are:
  - — 4 percent for the standard microturbine
  - — 8 percent for the advanced microturbine
  - — 20 percent for the standard engine
  - — 26 percent for the HTPEM fuel cell
  - — 30 percent for the advanced engine.

- Payback periods range from:
  - 4 to 5-plus years for HTPEM fuel cells, standard microturbines, and advanced microturbines
  - 2 to 3 years for both the standard and advanced engines.

Advanced Engine in Large Office Building – Various Cities (Figures 11 and 12):

Primary energy savings are 30 and 31 percent, and payback periods are 1.9 and 3.0 years, for Los Angeles and New York, respectively. Paybacks in the remaining cities exceed the payback threshold we imposed (5 years) for installation of CHP systems.

Various Building Types with Advanced Engine CHP Systems in New York (Figures 13 and 14):

- Primary energy savings at the economic-optimum capacities range from 30 to 35 percent
- Payback periods range from 2 to 3 years.

CONCLUSIONS AND RECOMMENDATIONS

CHP systems in commercial buildings can provide attractive end-user energy economics in high-utility-rate areas. While CHP can enhance the economic attractiveness of commercial building DG systems, it cannot compensate for low electric generation efficiency. High electric-generation efficiency remains essential to achieving attractive end-user economics. Other key conclusions are:

- An efficient CHP system can effect primary energy savings of up to 30 percent or more, while less efficient generation technologies (such as microturbines) have only modest impacts on primary energy use, ranging from a 3 percent savings to a 7 percent increase.

- Typically, installation of the distributed generation system accounts for 60 to 70 percent of the capital cost of a CHP system. The remaining 30 to 40 percent is for the absorption cooling equipment, heat-recovery heat exchanger, and ducting/piping, controls, and other balance-of-plant components.

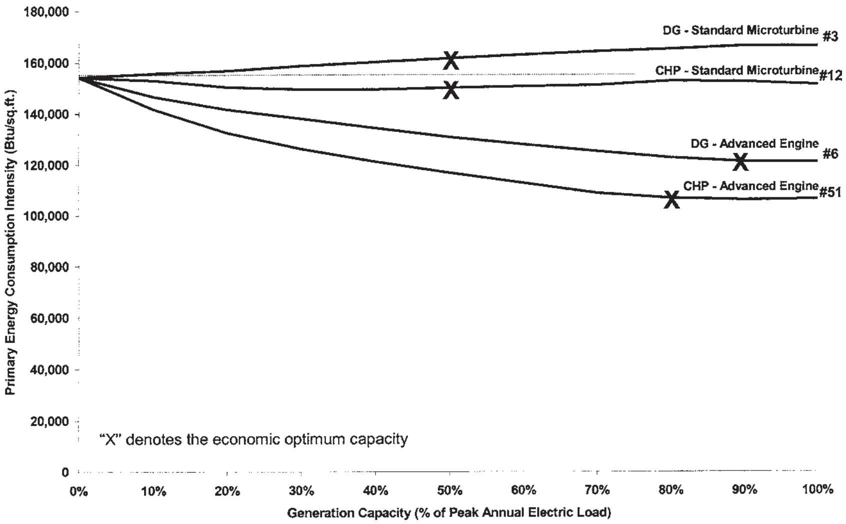


Figure 7. Primary energy consumption intensities for standard microturbine and advanced engine in New York office building—power only versus CHP.

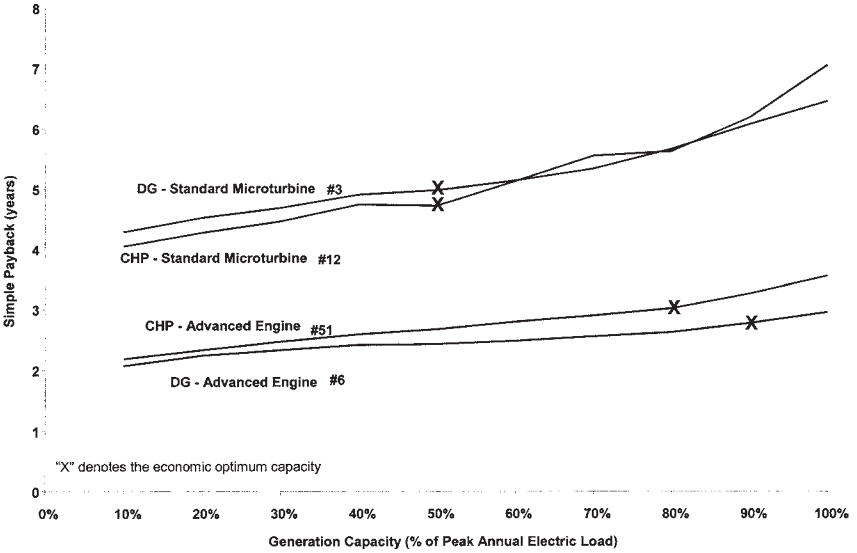


Figure 8. Simple payback periods for standard microturbine and advanced engine in New York large office building—power only versus CHP.

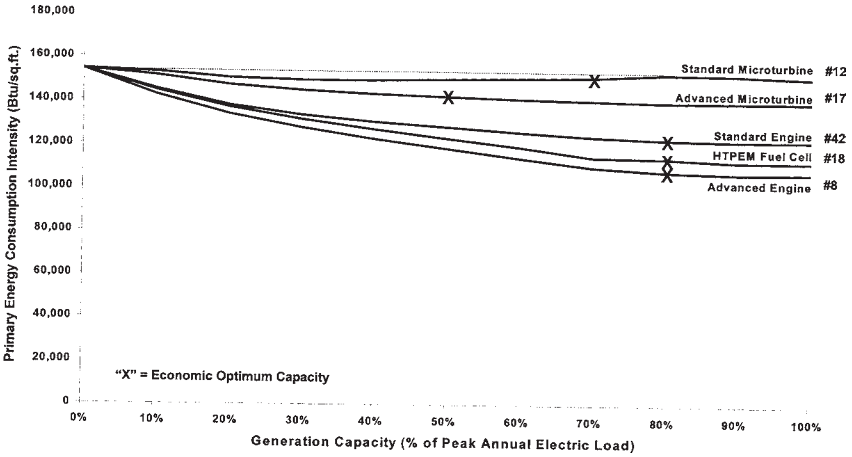


Figure 9. Primary energy consumption intensities for various CHP systems with generation technologies in New York large office building.

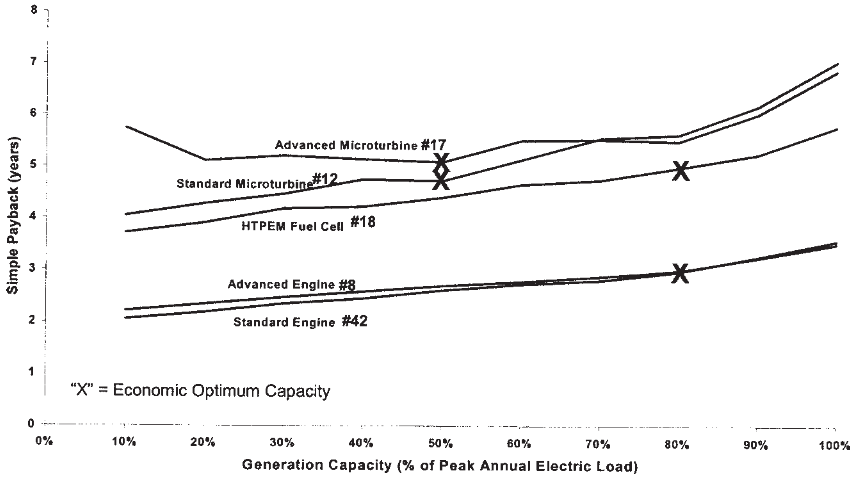


Figure 10 Simple payback periods for CHP systems with various generation technologies in New York large office building.

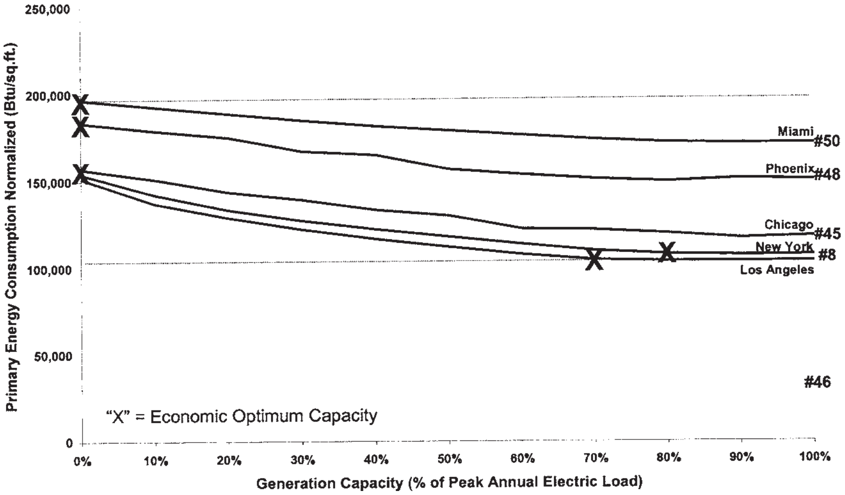


Figure 11. Primary energy consumption intensities for CHP systems with advanced engine in large office building for various cities.

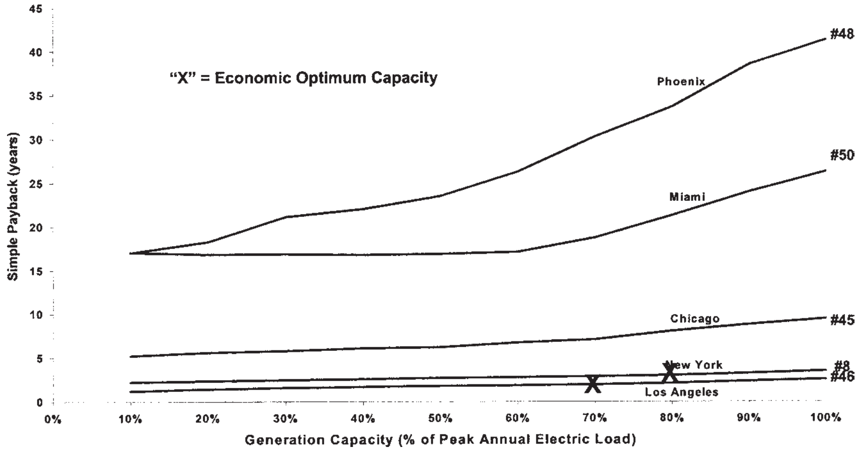


Figure 12. Simple payback periods for advanced engine in large office building for various cities.

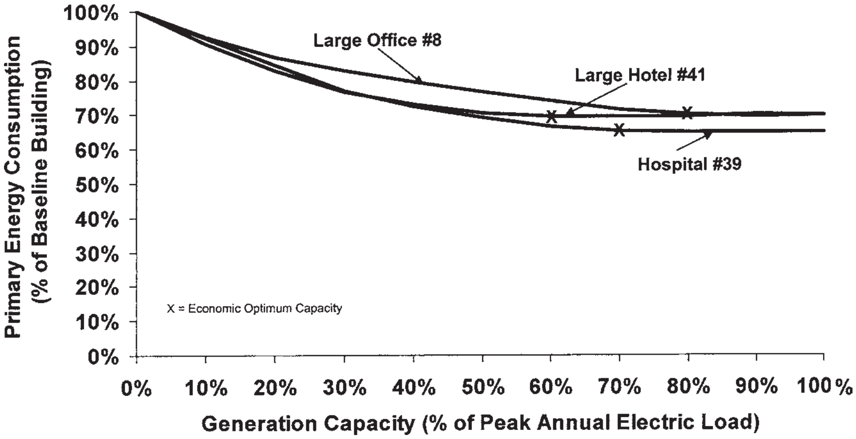


Figure 13. Relative primary engine consumption intensities for advanced engine CHP systems in New York for various building types.

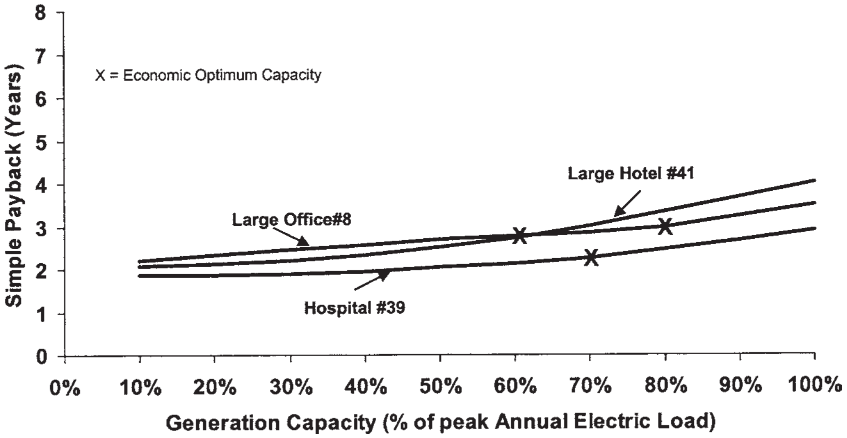


Figure 14. Simple payback periods for advanced engine CHP systems in New York for various building types.

- CHP system operating costs per kWh generated are often close to the electric energy charge (excluding demand charges) avoided. Therefore, small changes in operating costs or energy charges can have significant impacts on the economics of CHP.

In addition, there are several refinements in the analysis of energy savings and end-user economics that may be warranted. For example, heat recovery for absorption cooling from engines may be significantly more expensive than from other technologies (such as microturbines or combustion turbines). This is presumably associated with the difficulty of recovering heat from engine exhaust and jacket, compared to direct exhaust into an absorption chiller. Accounting for such costs would close the economic gap between CHP systems using engines and those using other prime movers.

Extending the analysis to light-commercial buildings is of interest. Light-commercial buildings typically use unitary HVAC equipment, which should improve the economics of heat recovery for cooling relative to buildings using electric chillers.

Extending the analysis to solid-oxide fuel cells (SOFCs) would also be of interest, given their promise of very high generation efficiencies combined with high-temperature exhaust streams (which may be attractive for heat recovery).

Some other potential refinements, although perhaps small in impact, include:

- Use higher efficiencies for double-effect absorption because there are no burner inefficiencies when driving the absorber with waste heat alone.
- Sizing the absorption chiller optimally, rather than sizing it to match peak waste-heat production.
- Assume a co-fired absorption chiller can displace some of the electric cooling plant, rather than assuming the absorption chiller must be redundant with existing cooling capacity.
- Account for part-load efficiency degradation and ramp-up/ramp-down characteristics of generation systems.
- Account for the impacts of unscheduled CHP system outages.

Most important, achieving broad market penetration in the commercial-building sector will depend on the extent to which evolving CHP business models can combine other benefits (power quality/reliability, T&D system support, and possibly emissions credits) with end-user energy-cost savings as the basis for making installation decisions. However, the value of these other benefits can be very difficult to quantify. In support of evaluating CHP business models, better and more quantified estimates are needed of the value of these other benefits.

ACKNOWLEDGMENTS

The work presented herein is essentially a synopsis of a detailed (but, to date, unpublished) analysis that TIAX[(13)] completed in April 2002 on behalf of the U.S. Department of Energy (DOE), Distributed Energy Program, and Oak Ridge National Laboratory (ORNL). This detailed analysis would not have been possible without DOE/ORNL funding and without the guidance of Ronald Fiskum of DOE and Robert DeVault of ORNL. Under the original DOE/ORNL project, Richard C. Williams, formerly of TIAX and now with Resodyn Corporation, and Sephir Hamilton, formerly of TIAX and now with Central Hudson Gas & Electric Corporation, developed the analytical model for this work, assembled input data for the model, ran an analysis matrix consisting of over 450 cases, and documented the majority of the work. Dr. W. Peter Teagan of TIAX provided critical senior review and guidance.

Richard Sweetser of EXERGY Partners provided valuable third party review and feedback.

END NOTES

(1) For electricity, primary energy accounts for the losses associated with generation, transmission, and distribution. For natural gas, primary energy accounts for the losses associated with transmission and distribution. However, these losses are small for natural gas, and are often neglected.

(2) The convention for power systems is to base efficiency on the lower heating value (LHV) of the fuel. In contrast, the efficiency of cooling and heating equipment is generally based on the higher heating value (HHV).

(3) See Table 1.

(4) Corresponds to about 81% (HHV) efficiency.

(5) HTPEM is not to be confused with conventional PEM, which is further along in development, but still just beginning to be commercialized. Waste-heat temperatures for conventional PEM typically range from 140 to 180°F, whereas waste-heat temperatures for HTPEM typically range from 220 to 320°F.

(6) An estimated 97 percent of the chiller market is electric chillers. Most of the remainder is absorption chillers, followed by a few engine-driven chillers. [3]

(7) Light-commercial cooling equipment does not necessarily consume more energy relative to large-commercial equipment. Large-commercial equipment has significant energy requirements associated with the distribution system, which we do not consider here.

(8) Of course, one might question if a building that uses electric-resistance heating would be likely to consider a CHP system. An end user sophisticated enough to consider a CHP system, and having fossil fuel available (as would be needed by the CHP system), would likely already utilize that fuel for heating – or at least evaluate it as an alternative to CHP.

(9) The peak electric load of the baseline building varies from that for the building using CHP because the heat recovered and utilized reduces the electric load on the building.

(10) While rebates and other incentives may be important elements in a program to promote CHP systems, we wanted to evaluate the fundamental economics of CHP.

(11) A logical way to include power-quality benefits in the economic analysis would be to subtract from the CHP system capital investment the capital investment avoided by not having to install back-up generators, uninterruptible power supplies (UPS), and other equipment that would be needed to provide similar power quality.

(12) One of the limitations of simple payback is that it does not provide a fair basis of comparison among mutually exclusive investments having significant differences in first costs. This is exactly the situation we have when comparing CHP systems of various capacities for a single end use.

(13) At the time the original analysis was conducted, TIAX was known as the Technology & Innovation Business of Arthur D. Little, Inc.

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[1] 2003 Building Energy Databook; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy; August 2003; Table 6.2.4.

[2] 481 Prototypical Commercial Buildings for Twenty Urban Market Areas; Lawrence Berkeley National Laboratory; published for the Gas Research Institute; June 1990; Pages 4.4-4.13.

[3] Foley, Gearoid; Presentation by Broad USA; December 5, 2001.

[4] DeVault, Robert; Oak Ridge National Laboratory; Cooling, Heating & Power Comparison. Excel spreadsheet. Updated March 29, 2001.

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