Combined Heat and Power (CHP or Cogeneration) for Saving Energy and Carbon in Commercial[1] Buildings

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ABSTRACT

Combined Heat and Power (CHP) systems simultaneously deliver electric, thermal and mechanical energy services and thus use fuel very efficiently. Today's small-scale CHP systems already provide heat, cooling and electricity at nearly twice the fuel efficiency of heat and power based on power remote plants and onsite hot water and space heating. In this paper, we have refined and extended the assessments of small-scale building CHP previously done by the authors. We estimate the energy and carbon savings for existing small-scale CHP technology such as reciprocating engines and two promising new CHP technologies--microturbines and fuel cells--for commercial buildings. In 2010 we estimate that small-scale CHP will emit 14-65% less carbon than separate heat and power (SHP) depending on the technologies compared. We estimate that these technologies in commercial buildings could save nearly two-thirds of a quadrillion Btus of energy and 23 million tonnes of carbon.

Introduction

Combined Heat and Power (CHP) systems simultaneously deliver electric and thermal energy and thus use fuel far more efficiently than separate heat and power (SHP) based on power remote plants and onsite thermal supply. In contrast to the delivered electric efficiency (after Transmission and Distribution (T&D) losses) of only 30%[2] or a best electric efficiencies of 50-55%, CHP systems now reach 90% fuel use efficiency (EIAb 1997; Major 1995). We estimate that these technologies in commercial buildings could save nearly two-thirds of a quadrillion Btus (Q or Quads) of energy and 23 million tonnes of carbon (MtC) (**Table** 7).

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[1] Due to a several recent developments (see, for example Wald, M. 1998. "Fuel Cell Will Supply all Power to a Test House." *New York Times*. June 17.) our planned residential CHP analysis is not included here. It will be available in August in a longer version of this paper to be posted at http://www.aceee.org.

[2] This efficiency and the others listed in this document refer to higher heating value (HHV)

Background

The higher efficiency of CHP depends on the Second Law of thermodynamics. A Carnot heat engine[3] must "reject" heat. A CHP system uses most of the rejected heat and all the power. CHP in buildings is the smallest scale used for exploiting the rejected heat from electric generation. Other CHP technologies that use heat from electricity generation in buildings include district energy systems (10MW-utility-sized) and industrial cogeneration (5-100MW)(Spurr 1997, Interlab 1997). This paper examines the potential for small-scale (<1MW) building CHP. With improvements in smaller technologies lowering both initial and maintenance costs, CHP use in single buildings will increase. The final step may be to scale fuel cells down to ~1kW size for a single house, but we limit our analysis to the commercial sector.

Motivation for Buildings CHP

None of the other recent studies that examine the potential of CHP to save energy and reduce carbon comprehensively examines available and soon-to-be-available small-scale (less than 1 MW) CHP for US buildings (summarized in DOE/EPA 1997). This is understandable is light of the current small installed capacity (< 5GW) of small-scale CHP, but we believe dramatic growth in this area is possible. Small-scale CHP will soon be a greatly updated and transformed technology. In the next two or three years, many new, more efficient, and lower-cost small CHP systems will become available (Kaarsberg & Elliott 1998). Although CHP is well established in industry, building energy experts still view it as an unproven technology. For small-scale CHP to achieve a significant penetration of the building sector, there will have to be some effort devoted to demonstrating its reliability and cost savings to potential users. In addition, all CHP technologies must overcome the many barriers detailed in the references (DOE/EPA 1997; Kaarsberg et al. 1998; Munson & Kaarsberg 1998).

Separate Heat and Power (SHP)

Table 1 shows heat and electric efficiencies for separate heat and power technologies used in our analysis. Current and future small-scale CHP is more efficient on a system basis (80- 90% efficient) than even the best current and future separate heat and power (SHP) technologies.

Table 1. Efficiencies (η) of Conventional Separate Heat and Power (SHP) Technologies. Source: (EIAb)

Separate Heat and Power (SHP) Technologies	Heat η	Electric η	System η
New, Utility-sized Combined Cycle Gas Turbine including T&D losses	N/A	51%	51%
Current U.S. grid including T&D losses	N/A	30%	30%
Typical New Gas Furnace	80%	N/A	80%
New Gas Water Heater	65%	N/A	65%

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[3] essentially all combustion-based electric generators are Carnot heat engines. Fuel cells also reject heat.

Recent Developments in Small-scale CHP

Commercial buildings that now use CHP tend to be large, high occupancy buildings with large thermal (especially hot water) loads such as hotels and hospitals. The thermal to electric (T/E) ratio[4] of such facilities is typically greater than 1.4--well matched to available engine-based package CHP units. Recently, utility barriers such as high exit fees and backup charges have led to a decline in small-scale CHP in some states(Kaarsberg and Munson 1998). Small-scale CHP is expected to encounter increasing problems with environmental permitting because state and regional air authorities require expensive end-of-pipe control technologies that can add 25% to the CHP's cost. (Onsite 1998.) But two new small-scale CHP technologies, fuel cells and microturbines, are generating great interest from the media and Wall Street. The small-scale market should also be helped by service innovations. Beyond maintenance contracts, companies have expanded CHP services to include financing and environmental permitting.

Characteristics of Small-scale CHP

This section describes current CHP technologies such as reciprocating engines and also two smaller, quieter and cleaner technologies on the horizon. It also describes a heat-driven chiller technologies that use CHP heat instead of electricity for chilling. Each technology aces barriers detailed in the following and in the section on future market estimates.

Reciprocating Engines ("Engines")

In such systems, the engine drives an electric generator while the heat from the engine exhaust, cooling water and oil generates steam in a boiler. Package systems of less than 100 kW have been available in the U.S. since the early 1980s. Cummins Diesel and Caterpillar both manufacture CHP package systems down to 25 kW--about the size needed for a fast-food restaurant. When measured on a performance basis (i.e., including thermal energy in the denominator), the NOx emissions of a modern engine, 0.5 $\text{lb/MWh}_{(t+e)}$ are fairly low, but still higher than the other two technologies'(Kaarsberg & Bluestein 1998). These emissions, along with the greater noise and size of the engines, limit their applications. Still, engine-based systems will continue to be the lowest cost option (about $300/kW) for small-scale CHP in the near term. The outlet temperature of an engine, less than 120 °C, is too low to run more efficient double and triple-effect chillers.

Fuel Cells (FCs)

There are four different fuel cell technologies under development, the phosphoric acid fuel cell (PAFC), the proton exchange membrane fuel cell (PEMFC), the molten carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). All are based on chemical reactions that produce an electric current and heat. The only fuel cell commercially available in the U.S. is a 200 kW PAFC--almost all of which are operated in CHP mode (DOE/FE 1997). Fuel cells produce negligible amounts of pollution (e.g. NOX at 0.005 $\text{lb/MWh}_{(t+e)}$), operate at very high efficiency (up to 45% electric) and because they have no moving

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[4] T/E is in units of site thermal divided by site electricity use.

parts, are very quiet. A major barrier to fuel cells is their first cost--now about $3000/kW. Even though two high-tech markets, transportation and telecommunications, are expected to speed cost reductions in small-scale (mainly PEM) fuel cells, lowering costs by an order of magnitude may be needed. The fuel cell is also limited by its greater sensitivity to fuel impurities than the combustion-based systems. The current outlet temperature of a PEMFC less than 100 °C, is too low to run any chiller except for the low-efficiency half-effect chiller for which it has never been used.

Gas Microturbines (μturbines)

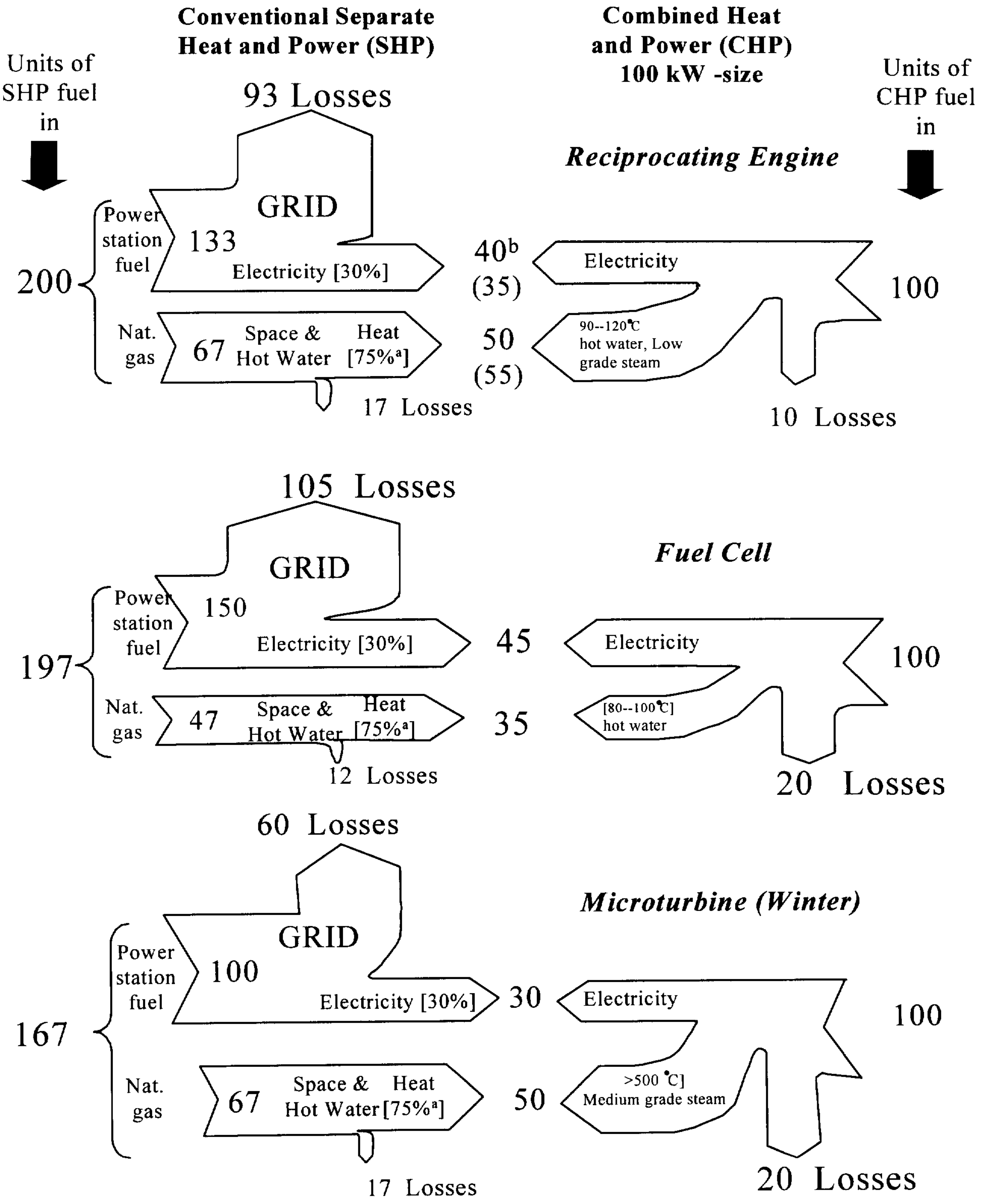
Currently, jet-engine-derived gas turbines are only cost-effective for systems down to 500kW (at $600/kW with $0.005/kWh maintenance.) This is already a significant size reduction for cost-effective operation from the turbines available even five years ago. By 2000, several μturbines (less than 100 kW) will enter the commercial power market. Capstone Turbine Corporation and AlliedSignal, Inc. expect to be selling very small (30 kW) turbines by 1999 and about a dozen other companies, including Ingersoll-Rand and Elliott Energy Systems, also are developing μturbines. In a recent 3,700 hour test of a 30 kW Swedish μturbine, more than 28% electric efficiency was achieved (Carnö et al. 1998). These turbines will be cleaner (0.25 $\text{lb/MWh}_{(t+e)}$) and quieter than comparably-sized engines (Capstone 1997). Microturbines' high outlet temperature (>500 °C) is suitable for numerous high-value applications including powering high-efficiency triple-effect absorption chillers. They are projected to sell at $250/kW with high-volume production.

Table 2a. Comparison of Three Different CHP Prime Movers Shown in Figure 1 (Source: Major 1995)

100 kW unit	Electric η%	Thermal η%	Temperature Range	System η%	T/E	SHP/CHP$|_{\text{fuel}}$
Engine (today's)	**40** **(35)**	**50** **(55)**	90--120 °C hot water, low-grade steam	**90**	**1.25** **(1.57)**	**2.00** **(1.65)**
Fuel Cell	**45**	**35**	80--100 °C hot water	**80**	**0.78**	**1.97**
μturbine	**30**	**50**	>500 °C medium grade steam	**80**	**1.66**	**1.67**

By 2010, **Table 2a** (last column) shows that both the engine and the fuel cell will be twice as efficient and the μturbine five thirds more efficient than today's separate heat and power. On the left hand side of **Figure 1** is the SHP needed to match 100 units into each of the three CHP technologies in 2010. **SHP/CHP**$|_{\text{fuel}}$ can be read off the left hand side of figure 1. It is the SHP fuel needed to produce the same amount of electricity and thermal energy as the CHP unit. Figure 1 graphically summarizes all the information in Table **2a**.

Figure 1. Characteristics of Three Different CHP Prime Movers (whose properties are also summarized in **Table** 2, compared with SHP summarized in **Table** 1. These correspond to Cases 6,7 and 8 (winter)



a. 75% is the average of 2 units of space heat from an 80% efficient boiler and 1 unit of water heat from a 65% efficient water heater

b. 40% in 2010, 35% today

Absorption Chillers

Instead of using mechanical energy, absorption chillers use heat to provide a working fluid (the refrigerant), which can be expanded and cooled as part of a refrigeration cycle (FEMP 1997). For example, in a lithium bromide/water absorption cycle, heat drives water vapor out of a LiBr solution (the absorbent) under a vacuum (P1=0.07 atmospheres). The water vapor is then cooled to ambient temperature and condenses (still at P1); then it is further cooled by expansion to a ten-times lower pressure (P2) where it condenses by extracting heat from the cooling load. Finally it is pumped back into the LiBr solution, where it is reabsorbed due to its chemical affinity with LiBr. **Table** 2b shows the range of thermal COPs and temperatures for various chillers. (Devault 1998; Erickson 1996).

The most efficient triple-effect chillers are in the same range as the COP of an electric chiller, in terms of primary energy. However, because absorption chillers' first cost is higher-- per ton (i.e., for 3.5 kW of heat extraction) installed, it is $900 vs. $350 for electric chillers--heat-driven absorption chillers now comprise a fairly small portion of the chiller market. Of these, most are gas-fired. The few that are waste-heat driven are almost exclusively single-effect chillers. Of the small-scale CHP technologies, only turbines have outlet temperatures high enough to drive double- and triple- effect chillers. Thus, the commercialization of μturbines will greatly expand markets for CHP to such non-traditional markets as office buildings with their large cooling loads.

If CHP heat is available in a new building without existing chillers, it will pay[5], on a life-cycle basis, to invest in absorption chillers for turbines and possibly for the other technologies. In an existing building, however, early retirement of an existing electric chiller may not be cost effective. However, lack of CFCs (i.e., expensive CFC replacement) for electric air-conditioning is likely to lead to improved relative economics for absorption chillers. Despite a phase out of production of ozone-depleting chlorofluorocarbon (CFC) refrigerants completed in 1995, many centrifugal and screw compressors still use them. A recent survey showed that approximately 70 percent (at least 56,000) of the chillers that used CFCs in the early 1990s remain dependent on CFCs (ARI 1998). Simultaneously, new technologies, such as highly efficient triple-effect absorption chillers (COP >1.7) are about to enter the market.

Table 2b. Characteristics of Four Different Absorption Chillers. Source (Devault 1998; Erickson 1996).

Chiller Type	**Thermal COP**	**Temperature Range °C**
Half-effect	**0.35**	**80 - 100**
Single-effect	**0.70**	**100 - 120**
Double-effect	**1.1**	**150 - 170**
Triple-effect	**>1.6**	**170 - 200**

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[5] using a 6 % real discount rate.

Estimate of Potential Savings from Building CHP Technologies

We begin with the technical potential based on electric and thermal demand. We then calculate savings based on the properties of each small-scale CHP technology.

Maximum Technical Potential

Table 3 shows 1996 electric and thermal energy used by U.S. commercial buildings. It compares this with the electricity supply and the waste heat from power plants.

Table 3. Comparison of Buildings' Demand for Heat and Supply of Heat from Electricity Generation

	Type	A. Site Electricity (Quads)	B. Heat (Quads)
1	*Residential*	*3.7*	*7.4*
2	*Commercial*	*3.4*	*11.6*
3	Total Demand	7.1	19
4	**Power Supply**	**7.1**	**16 (now unused)**

Source(EIAb 1997)

The 7.1 Quads of site electricity provided to buildings (A4) now generates 16 quads of waste heat (B4), only 3 Quads less than the total building heat demand (B3) of 19 Quads. If the electricity used in buildings were generated by self-powered buildings operating at 30 percent electric efficiency (the same efficiency as electricity delivered from the grid) that also used the waste heat, it would represent a theoretical 83% drop in building energy consumption. Thus, the technical potential for building CHP to save energy is enormous. The problem is how to do this most cost-effectively. The analysis to follow examines such options and how we might approach this 83% potential savings.

Estimates of Energy and Carbon Savings Based on Three Building Energy End Uses.

In this section we examine the inputs (**Table 4**) and the results (**Tables 5&6**) of a simple calculation of savings from CHP for high-occupancy, heat-intensive buildings on the electric and gas grids (e.g., hospitals or hotels). Because these buildings operate seven days/week, they will be early CHP clients. The only building energy characteristic that enters our calculations is the shape of the daily profiles for electricity and heat, both space heat and hot water (ADL 1995).

Although **Table 6** includes three technologies and two markets, for the purpose of describing our method and nature of the results, we discuss just one (engine) of the three technologies. Consider a 100 kW_e unit (and scale up the tables to macro units, i.e., 1 GW installed in the U.S.). This 100 kW_e engine supplies 140 kWh_t of heat. We assume that one or more of these units will roughly match the winter heat demand profile, with backup boilers filling in on the coldest days, and that some electricity will be bought or sold as needed. Over six months of "winter" (the heating season) we assume that our engine serves its load at a 75% duty factor. In "summer" (the six-month cooling season), engines' and fuel cells' outlet temperatures are too low to operate an absorption chiller, so we halve their duty factor (assuming only production of hot water) for 6 months. The yearly average duty factor is then three quarters of 75 percent of the year, this corresponds to 4,928 hours/year, and generation of 493 MWh_e. **Table 4** summarizes the assumptions for all eight cases.

Table 4: Assumptions for Technology Comparisons in Tables 5 and 6

A. CHP Technology		**B. Displaced SHP Site Electricity (Power)**	**C. Displaced SHP Thermal (Heat)**
(1) Today's Engine		Today's Grid (182g/kWh)	Electric space & water heating in retrofits
(2) Today's Engine		Today's Grid (182g/kWh)	Gas space and water heating in new and retrofitted buildings
(3) 2010 Engine		CCGT (97g/kWh)	“
(4) 2010 Fuel Cell		CCGT (97g/kWh)	“
(5) 2010 μturbine	Winter	CCGT (97g/kWh)	“
	Summer	CCGT (97g/kWh)	Electric (COP=3) space cooling in new buildings [replaced with waste-heat- powered Absorption Chiller (COP=1.6)]
(6) 2010 Engine		marginal coal (289g/kWh)	Gas space and water heating in new buildings
(7) 2010 Fuel Cell		marginal coal (289g/kWh)	“
(8) 2010 μturbine	Winter	marginal coal (289g/kWh)	“
	Summer	marginal coal (289g/kWh)	Electric (COP=3) space cooling in new buildings [replaced with waste-heat- powered Absorption Chiller (COP=1.6)]

Today's Technology and a Case Study.

Small-scale CHP units already have a successful track record in a wide range of building applications. Because existing small-scale CHP technology has a relatively high T/E ratio (55/35=1.4), it has been most successful in situations with a large hot water demand, such as colleges, hotels, hospitals, and some restaurants. (See Major 1995 for an excellent set of case studies.) The purpose of this section is to show that CHP benefits are not solely, or even mainly, dependent, upon the success of new, yet-unproven technologies.

Today's Cases. More than 600 small engine-based CHP systems have been sold as convenient skid-mounted package units since the 1980s (Tecogen 1997). In both cases described below, the engine displaces electricity from the current, 30% efficient delivered, U.S. grid (11,400 Btu/kWh_e, and 182 gC/kWh_e, after correction for T&D losses). In *Case 1,* the CHP heat replaces electric resistance heat (and electric chilling). It is the most obvious, highest payback CHP retrofit. The Waverly Junior-senior high school case study below, is such a case. There are many more such opportunities, electric resistance provides 10% of space heat in us commercial buildings. In *Case 2*, the CHP heat displaces natural gas burned at 80 percent efficiency for space heat and 65 percent efficiency for hot water. This would be the case for a new building or most retrofits.

Table 5: Energy and Carbon Use and Savings for Today's Small-scale CHP Technologies, for 1 GW_e of Installed Capacity. Cases (1)&(2) are Defined in Table 4.

CHP Technology	**Primary Energy in TBtu, for 1 GW_e Running 4,928 Hours/year (A)**				**Energy Savings**	**Carbon Avoided**	**Carbon in MtC per Installed GW_e**			
	CHP Fuel	**SHP** Electric (Table 4, Col. B)	**SHP** Heat (Table 4, Col. C)	**Savings (SHP-CHP)**	**Δ% (B)**	**Δ%(B)**	**CHP Fuel**	**SHP** Electric (Table 4, Col. B)	**SHP** Heat (Table 4, Col. C)	**Savings (SHP-CHP)**
(1) Today's Engine-I^2R retrofit	48	56	84	92	66%	69%	0.7	0.89	1.34	1.53
(2) Today's Engine-new Bldg.	48	56	20	28	37%	41%	0.7	0.89	0.29	0.48

(A) As discussed just above **Table** 4, the engine is assumed to run at a 75 percent duty factor (e.g. for a Hotel or Hospital) for six winter months and at 37.5 percent duty factor for six months of summer because the engine's thermal output (less than 120°c) is generally considered insufficient to run a chiller. This is 4,928 hours per year per GW or 4.9 TWh_t.

(B) Δ% Defined as (SHP-CHP)/SHP

Table 5 presents "Today's" results, not for a 100 kW Unit, but scaled up to 1 GW of installed capacity (so 490 MWh_e becomes 4.9 TWh_e). The most interesting results are the two center columns: "Energy Saved" and "Carbon Avoided." Thus for *Case 1*, the CHP engine uses 66% less fuel and generates 69% less carbon than SHP with electricity and (resistance) heating from the current grid. For *Case 2*, the CHP engine uses 37% less fuel and generates 41% less carbon than the current grid for electricity and gas space and water heating.

Waverly High School Case Study. The **all-electric** Waverly Junior-Senior High School in New York was built in 1967. The school, a 200,000 square foot, two-story building, had been designed for \$0.01/kWh and kWh per year. As electricity prices rose, the school reduced its use to 2,500,000 kWh per year in 1986 through demand-side reductions (Robbins, 1998). It had, however, reached the limit of these reductions. The thermostat was turned down in winter and off in the summer. But power costs for the school, in a high-electricity-cost area (\$0.075/kWh) were more than \$180,000 per year. The school superintendent commissioned a study of a CHP system to supply the school's thermal and electric needs. The study confirmed pay back of less than three years for an electric-load following, 375 kW_e CHP system.

Still, the school board was hesitant to invest. Representatives of the local utility, Pennsylvania Electric Company (PENELEC), who came to school board meetings, opposed the proposal. To convince the board and the county's taxpayers to invest in CHP, it took an external technical assessment, several internal studies, traveling to other cogeneration sites, additional administration studies and finally a \$365,000 Energy Conservation grant from the New York State Energy Office. Manufacturers had sold hundreds of these units that operated reliably since they were introduced in the early 1980s. The grant was not even necessary for the project to be economically attractive.

When finally installed, the project was almost an instant success, it paid itself off in 27 months and it won the 1993 Governor's Award for Energy Excellence given each year by the New York State Energy Office and The New York Power Authority for energy-efficiency, innovation and education. In 1998, after eight years of operation of its five Tecogen 75 kW Engines, the school, and the 10,000 taxpayers in the Waverly school district, are saving more than $100,000 per year (60%) from avoided electricity use. The one thousand students and staff who use the school are also more comfortable because the temperature is more consistent. The environment also benefits. Annual carbon emissions compared to average SHP, are 250 tC (Brown M. et al. 1998). This reduction is equivalent to taking 250 cars off the road, or all the cars in the school parking lot plus 50 visitors. These savings are due to the use of the waste heat from the onsite electricity generation to replace the inefficient use of electricity for making hot water and space heating. Because hot water, heating, and chilling are now provided from the CHP thermal output, the electricity used by the school is a fraction of the previous usage. Electricity generated by the CHP unit is used only for lighting, computer, motors and office equipment. Besides saving energy, the CHP package system is easy to maintain and requires no additional personnel to operate it.

The Waverly project demonstrates a unique combination of off-the-shelf technologies: the electric-load following cogeneration units are coupled to a device that tracks the electric loads of the building. Thermal output is directed to a new hydronic system that distributes heat to space heating and ventilating systems, pool water heating, domestic water heating, and in the cooling season, a hot water-activated absorption chiller (Trane 1996). The project also clearly demonstrates that substantial efforts are needed to overcome utility and perceptual resistance to even the most cost-effective CHP technologies.

New Technologies in 2010

Introduction of high-temperature ceramics and other advances in combustion technology will continue to increase electric efficiencies for both engines and turbines. Thus, in the 2010 scenarios, we raised the estimated electric efficiency of the engine to 40% and that of the μturbine to 30% from today's figures. We also raised the fuel cell electric efficiency to 45% from today's maximum 40% electric efficiency. In summer, because the μturbine can run an absorption chiller, thus displacing peak electricity used for cooling we assume it runs 6,570 hours/year. We make the conservative assumption that engines and fuel cells will not be routinely running chillers in 2010. This amounts to assuming that the engine temperatures remain too low and that the dominant small-scale fuel cell technology is the low temperature PEM fuel cell, as shown in figure 1. Thus, the engine and the fuel cell run 4,978 hours per year as assumed in today's case. In examining the range of possibilities and other studies, we have concluded that the variation in the SHP technologies used for comparison could be greater than the variation in CHP technology. Thus, in **Table 6**, we provide two extremes of SHP technology. In **Table 7**, we use the average of these two to estimate savings.

2010 Cases 3-5--"Business-as-Usual" (BAU) Scenario. This case assumes 1) little national emphasis on energy conservation, specifically electricity conservation, 2) that energy prices remain low, 3) and that there is no incentive to shut down coal plants such as a carbon cap-and-trade system or strict mercury emissions standards. We compete a new 55 percent efficient utility-sized combined-cycle natural gas turbine (CCGT) on the grid (6,700 Btu/kWh$_e$ and 97 gC/kWh$_e$ after T&D losses) and gas hot water and space heating (and for the μturbine, electric chilling) with all three new CHP technologies. **Table 6**, which is in the same format as **Table 5**, shows energy saving even when CHP competes against the lowest-carbon

SHP fossil technology. For example, for case 3, the 2010 engine uses 14% less fuel and generates 14% less carbon than separate CCGT for electricity, electric cooling and gas space and hot water heating.

2010 Cases 6-8--High Efficiency/Low Carbon Scenario. This case assumes 1) a vigorous national commitment to energy efficiency so that there is little demand for large increments of power and gas prices remain low, and 2) that we institute carbon reducing policies that make coal less attractive. We compete an old (retiring) coal plant on the grid (11,400 Btu/kWh_e like today's grid, but 290 gC/kWh_e after T&D losses) and gas space & hot water heating (and for the μturbine, electric chilling) with all three new CHP technologies. This assumption, that coal plants are retiring in 2010, comes from the "5-lab report's" high efficiency/ low-carbon scenario, in which conservation and carbon permit trading are competing with coal plants (Interlab 1997). The μturbine here (8) uses 39% less fuel and generates 63% less carbon than separate heat and power using retiring coal plants for electricity.

Table 6: Energy and Carbon Use and Savings for Three 2010 Small-scale CHP Technologies, for 1 GW_e of Installed Capacity. Cases (3)-(8) are defined in Table 4.

CHP Technology (in 2010)	Primary Energy in TBtu (a)				Energy Savings	Carbon Savings	Carbon in MtC per installed GW			
	CHP fuel	SHP fuel (Table 4, col. B)	SHP Heat (Table 4, col. C)	Savings (SHP-CHP)	Δ%	Δ%	CHP fuel	SHP fuel (Table 4, col. B)	SHP Heat (Table 4, col. C)	Savings (SHP-CHP)
BAU Scenario (vs. CCGT)										
(3) Engine	42	33	16	7	**14**	**14**	0.61	0.48	0.23	0.10
(4) Fuel Cell	37	33	10	5	**13**	**13**	0.54	0.48	0.14	0.08
(5) μturbine[a]	75	44	33	3	**4**	**4**	1.09	0.64	0.49	0.04
High Efficiency/Low-Carbon Scenario (vs. marginal coal plants)										
(6) Engine	42	56	16	30	**41**	**63**	0.61	1.43	0.23	1.04
(7) Fuel Cell	37	56	10	28	**43**	**65**	0.54	1.43	0.14	1.02
(8) μturbine[a]	75	75	47	47	**39**	**63**	1.09	1.90	1.05	1.86

(a) 1GW= 6.6 TWh_e for μturbines because its heat clearly can run an absorption chiller, so μturbines can run year round at the 75% duty factor and thus 1 GW generates 6.6 TWh_e in a year. For engines and fuel cells 1GW=4.9 TWh_e as in Table 5.

2010 Market Estimates for Building CHP Technologies

Because of uncertainties in future policies, and in future technologies, we are reluctant to predict the exact mix of technologies and fuels that might deliver carbon savings by 2010. But as seen above, potential impacts could vary significantly depending on this mix. Thus, in this section, we do examine energy and carbon results for a plausible set of market penetrations, recognizing the large uncertainty. **Table** 7 presents a possible set of market penetrations for 2010. These market estimate ranges are not a result of our analysis, but are extrapolations from others' estimates.

Engine. For this technology, **Table 7** presents new, additional, not total capacity. Based on information from institutional small-scale CHP the estimate in **Table 7** represents a range from no increased capacity to roughly double the projected capacity for small-scale CHP (Pierce 1998). From the point of view of energy and carbon, we have shown that engine-based CHP is cleaner and more efficient than even the newest SHP systems. Without environmental regulatory reform, however, engine-based CHP could even decline in the US as regulators require expensive end-of-pipe controls (Kaarsberg & Bluestein 1998). These excessive requirements come about in two major ways. First, when engine-based CHP replaces an electric-only generator, regulators unfairly compare its criteria pollutant to the state-of-the-art utility-sized electric-only technologies and give no credit for avoided thermal emissions. When CHP replaces a boiler or other thermal technology, regulators give no credit for avoided electric grid emissions, which, as shown in Figure 1, are the major part of the emissions reduction.

Fuel Cell. Given that the total installed capacity of fuel cells in the US is currently less than 10 MW, this 5-10 GW estimate represents remarkable growth in small fuel cell capacity (FEMP 1997). Our high 2010 market figure in **Table** 7 comes from an ADL analysis for the 5-lab study. We assumed the scenario that predicted additional transportation R&D could reduce costs to $700/kW by 2010. This now seems a plausible assumption; fuel cell technology was recently chosen by the major American car makers as a finalist for the 3X efficiency (50-100kW) car being developed as part of the Partnership for a New Generation of Vehicles (DOC 1998). One of the PNGV FC research goals is to increase the temperature of the PEMFC. This could have the serendipitous effect of making it possible to run an absorption chiller for PEMFC in building applications. However, the PEMFC is unlikely to exceed 120°C by 2010 and would thus be marginal for driving an absorption chiller. Fuel cells ranging in size from 1 kW up to several megawatts are being commercialized for niche, early markets such as premium power for telecommunications and remote power. Three U.S. and several foreign companies are developing fuel cells suitable for self-powered buildings.

μturbine. The upper limit of our estimate is based on several manufacturers' estimates for world markets, our s-curve fit and the U.S. fraction of world generating capacity in 2010 (AlliedSignal 1998; EIA 1998; Stein 1997). Many investors including General Electric, which bought Elliot Engine systems, and General Motors, which recently announced a μturbine partnership with Wilson, are bullish on μturbines. Some, perhaps including Capstone investor Bill Gates, see an analogy between microturbines and PCs. Since these turbines have only one moving part— most μturbines avoid mechanical losses and increase efficiency by mounting the turbine, compressor, and permanent magnet generator on a single shaft— the maintenance costs could be lower. The innovation that allows single shaft operation is an inverter that reduces the generator frequency from 1200 Hz to 50 or 60 Hz. Some μturbines also feature "air-bearings" that need no oil, water, or other maintenance. They also will be fuel-flexible, accommodating natural gas, diesel, and gasoline. Nevertheless, the first and maintenance costs may not reach the promised $250/kW and $0.005/kWh by 2010

Table 7: Market Range Estimates and Resulting Energy and Carbon Savings for Three Small-Scale CHP Technologies in 2010.

CHP Technology	**Installed GW Estimates**	**<SHP> Energy Savings (Quads)**	**<SHP> Carbon Savings (MtC)**
Engine	0 -- 5	0 -- 0.09	0 -- 2.8
Fuel Cell	5 -- 10	0.08 -- 0.17	2.8 -- 5.5
μturbine	10 -- 15	0.25 -- 0.37	9.5 -- 14.2
Total	15 -- 25	0.33 -- 0.63	**12.3 -- 22.6**
% 2010 Baseline	5 -- 11%	2 -- 4%	4 -- 8%

Table 7 shows that savings from small-scale building CHP can approach 10% of the total 2010 emissions for commercial buildings. This is nearly 6 percent of the total, or 37% of commercial buildings' proportionate share, of the reductions needed for the U.S. to reach the Kyoto Treaty emissions levels. (Kyoto 1997; EIAa 1997).

Conclusion

We now have shown that off-the-shelf CHP technology is already an important technology for saving energy and carbon in commercial buildings. In addition, we expect that more efficient, versatile small CHP systems just coming on the market will be a significant improvement over even the best state-of-the-art separate heat and power technologies. We estimate carbon savings of 13-23 MtC by 2010 with corresponding energy savings of ⅓-⅔ Quads.

Because of a nexus of three factors, 1) current and impending improvements in small-scale CHP, 2) electricity deregulation, and 3) climate change concerns, small-scale building CHP is an important opportunity. To capture this opportunity, building energy experts must consider both supply-side and demand-side energy use reduction. An integrated approach to saving energy on both sides of the electricity meter will enable the most productive, and lowest carbon use of electrical, mechanical and thermal energy in buildings.

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Glossary

3X	"Three times" refers to a car three times more efficient that current cars (PNGV goal)
C	carbon-equivalent = 12/44* mass of CO_2
CO_2	carbon dioxide, a major greenhouse gas.
CADDET	Center for the Analysis and Dissemination of Demonstrated Energy Technologies
CCGT	combined-cycle gas turbine--the most efficient electricity generator available
CFC	chlorofluorocarbon -an ozone-depleting gas, now banned, previously used for chilling.
CHP	combined heat and power; a.k.a. cogeneration, also a subset of "self-powered buildings."
gC/kWh_e	grams of carbon equivalent per kilowatt-hour electric
GHG	greenhouse gas -NOTE: carbon dioxide, is the most significant anthropogenic GHG.
GW	gigawatt - 1,000,000,000 Watts
kW	kilowatt - 1,000 Watts
kWh_{t+e}	kilowatt-hour of combined electric (e) and thermal (t) energy expressed in electric units
lb/MWh	pounds per megawatt-hour--a performance-based or output-based environmental standard
M	million (when used with units of measure)
MCFC	molten carbonate fuel cell
MtC	million metric tonnes of carbon equivalent (a.k.a. MMTCE)
MWh	megawatt-hour = the energy generated by a 1,000,000 Watt generator in an hour
NOx	nitrogen oxides, a regulated smog precursor associated with fossil combustion
PAFC	phosphoric acid fuel cell
PEMFC	proton exchange membrane fuel cell
PNGV	Partnership for a New Generation of Vehicles-an industry government R&D partnership.
SOFC	solid oxide fuel cell
t	metric ton (or tonne = 1.1 English tons)
TBtu	tera-Btu = 10**12 Btu (British thermal units)
TWh	terawatt-hour = 10**12 Wh (Watt-hours)