An Integrated Assessment of the Energy Savings and Emissions-Reduction Potential of Combined Heat and Power

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ABSTRACT

Combined Heat and Power (CHP) systems, or cogeneration systems, generate electrical/mechanical and thermal energy simultaneously, recovering much of the energy normally lost in separate generation. This recovered energy can be used for heating or cooling purposes, eliminating the need for a separate boiler. Significant reductions in energy, criteria pollutants, and carbon emissions can be achieved from the improved efficiency of fuel use. Generating electricity on or near the point of use also avoids transmission and distribution losses and defers expansion of the electricity transmission grid. Several recent developments make dramatic expansion of CHP a cost-effective possibility over the next decade. First, advances in technologies such as combustion turbines, steam turbines, reciprocating engines, fuel cells, and heat-recovery equipment have decreased the cost and improved the performance of CHP systems. Second, a significant portion of the nation's boiler stock will need to be replaced in the next decade, creating an opportunity to upgrade this equipment with clean and efficient CHP systems. Third, environmental policies, including addressing concerns about greenhouse gas emissions, have created pressures to find cleaner and more efficient means of using energy. Finally, electric power market restructuring is creating new opportunities for innovations in power generation and smaller-scale distributed systems such as CHP. Our integrated analysis suggests that there is enormous potential for the installation of cost-effective CHP in the industrial, district energy, and buildings sectors. The projected additional capacity by 2010 is 73 GW with corresponding energy savings of 2.6 quadrillion Btus, carbon emissions reductions of 74 million metric tons, 1.4 million tons of avoided SO_2 emissions, and 0.6 million tons of avoided NO_x emissions. We estimate that this new CHP would require cumulative capital investments of roughly $47 billion over ten years.

Introduction

From the late 1970's to the early 1990's, CHP, or cogeneration, grew steadily, especially in the process industries. A significant factor in this growth was the passage of the Public Utilities Regulatory Policy Act of 1978 (PURPA). By the mid-1990's, CHP provided nearly 45 GW of industrial electricity generation capacity, or about seven percent of the U.S. total. Only three manufacturing industries accounted for 85% of all cogenerated electricity in 1994. However, since the mid-1990's, installation of new CHP has slowed dramatically. This deceleration is due to many factors, one of which was passage of the Energy Policy Act of 1992. This law allowed unregulated, independent power producers access to the electricity grid for wholesale transactions, a privilege previously reserved for cogenerators. More recently, uncertainties and policies associated with electric utility restructuring and impending stringent air regulations have discouraged CHP expansion. Unless these barriers are addressed through policy changes, this downturn is anticipated to persist (Elliott & Spurr 1999).

Ironically, this climate of impeding regulations and general deceleration of CHP in the U.S., comes at a time when worldwide studies, focusing on the role of energy efficiency in greenhouse gas (GHG) emissions reductions, have identified CHP as one of the most promising, cost-effective options. Acting on these studies, the European Union has planned for 20 percent of their GHG reductions to come from increased deployment of CHP. The United Kingdom plan, released in the fall of 1998, assumes as much as 50 percent of industry reductions will come from CHP applications. The authors' previous studies of various CHP market segments in the U.S. (industry, district energy, and commercial buildings) describe a window of opportunity for implementation. As the commercial and industrial boilers and electric power plants of the "baby-boom" retire, new or updated highly-efficient and lower-cost CHP systems could be built to replace them (Alliance et al. 1997; Elliott & Spurr 1999; Kaarsberg & Elliott 1998; Kaarsberg et al. 1998; Kaarsberg & Roop 1998; Spurr 1998). Clearly, policies in the U.S. that discourage CHP are working against substantial, cost-effective emissions reductions.

Coinciding with system retirements, and emphasizing the possibilities for CHP expansion, are the advancements of CHP technologies. New configurations now exist that reduce size yet increase output. Engines (and soon turbines) are, in some circumstances, cost-effective for CHP systems on the scale of tens of kilowatts, compatible to the size of a small office or restaurant. Equipment for even smaller applications is on the horizon. However, without rapid action, this opportune nexus of market, regulatory, and technological opportunities could dissipate. In this paper, we assume an optimistic policy scenario in which barriers discussed in other papers have been mitigated (i.e., Kaarsberg & Elliott 1998). We integrate our previous work and fill in gaps for a comprehensive, integrated analysis of the potential for CHP to save energy and reduce emissions by 2010.

Market Description and Outlook

The CHP market can be divided into three major sectors: industrial, district energy, and buildings. Each of these can be further subdivided. A detailed discussion of each sector, as well as their expectations for the future, follows.

Industrial

Background. The industrial sector represents the largest and best-characterized CHP segment in the United States. It is also the CHP segment with the greatest potential for near-term growth. The majority of this capacity exists in industrial sites with large steam loads. In 1994, three manufacturing industries, pulp and paper, chemicals, and petroleum refining, accounted for 85 percent of all industrial cogenerated electricity. Pulp and paper accounted for 41 percent or 59 TWh; the chemicals industry accounted for 33 percent or 47 TWH; and petroleum refining made up ten percent or 14 TWH of cogenerated electricity (EEA 1998). The CHP systems in these industries typically generate more than 25 MW of electricity (though sometimes hundreds of MW) and have steam generation rates that measure in the range of hundreds of thousands of pounds of steam per hour (EEA 1998). Much of this market was stimulated by PURPA, which allowed "qualifying facilities" to sell wholesale electricity. These plants are generally owned by an independent power producer that seeks an industrial customer for the steam, reducing their net operating costs in order to improve their competitiveness in selling electricity. The Energy Policy Act of 1992 created a new category of independent power producers that were not required to cogenerate, and as a result, installation of these merchant cogeneration plants has declined (EEA 1998).

Outlook. Although the larger industrial systems (>50 MW) currently dominate, analysts predict that if current market barriers are removed, both large and mid-sized (1 to 50 MW) industrial CHP facilities could expand rapidly in the next decade. The expansion of the mid-sized systems, a largely untapped market, is due to the confluence of several factors: new, smaller technologies; innovative energy service firms; and the need to replace thousands of boilers that provide process steam to smaller manufacturing plants. Replacing or repowering these boilers offers a large potential for adding new electricity generation capacity in the 1 to 50 MW size range. OnSite Energy recently completed assessments of the remaining potential for CHP in the pulp and paper, chemical, and food industry groups (1997a, 1997b, 1998). They identified a current potential of more than 36 GW of additional CHP from these sectors alone. The OnSite Energy analysis indicates that the food industry holds the greatest number of prospective sites in the 1 to 10 MW size range. Based on the above factors and evaluations, we assume that larger systems (>50 MW) will account for the majority of the capacity installed in the near future, with substantial midterm growth in the 1 to 50 MW size range. Rapid growth in the smallest systems (<1 MW) is expected only after current market barriers are addressed and new, lower-cost, highly-efficient, and low-emission small turbines, fuel cells, and engines are introduced.

District Energy

Background. District Energy Systems (DES) distribute steam and/or chilled water from a central plant (or plants) to a number of commercial, industrial, institutional, and even residential buildings. DES replaces on-site heating, domestic water heating, and sometimes air conditioning. This occurs when individual boilers and chillers, as well as electric heat, are replaced by heat exchangers or simply hot and cold water lines. There are roughly 6,000 DES systems in the U.S., providing 1.1 quads of energy and serving more than ten percent of commercial floor space (EIA 1995). About ten percent of these systems, or 3.5 GW, represent CHP/DES systems (Spurr 1998). CHP/DES schemes vary in size as much as they do in application. The range starts with community-based systems of several megawatts and stretches to urban projects such as the 150 MW scheme in Philadelphia.

Outlook. Most current DES customers are institutional, which means a single entity, such as a hospital, military base, or university, owns a group of buildings. These systems avoid many of the barriers which constrain the implementation of multi-user, utility district energy services. Despite the attractiveness of DES/CHP for institutions, the fastest growth in this sector is in urban downtown areas, particularly in cooling systems. Of the 23 new DES that have been built during the last 15 years, 14 have provided cooling only, six have supplied heating only, and three have produced cooling and heating (Spurr 1998). Eight of these new systems were implemented by municipalities and non-profit organizations, with the remainder developed by for-profit businesses (Spurr 1998). A number of factors have contributed to the interest in district cooling.

These include the ban on importation or manufacture of ozone-depleting CFC refrigerants, in effect since 1995, and the increasing energy cost of operating cooling systems. District energy systems can implement storage and load management strategies that can be prohibitively expensive in stand-alone facilities. In recent years, electric and gas utilities are increasingly implementing district cooling systems as competition increases for retail energy customers. While retrofitting an existing DES with CHP is an attractive way to add cost-effective CHP capacity, new DES are likely to grow very slowly because of the time and complexity involved in developing the piping networks, especially in multi-user schemes.

Buildings

Background. While the small-scale (<1 MW) CHP units have had a successful track record in Europe in a wide range of building applications, this sector is currently the smallest CHP sector in the United States. Sites with a large hot water demand, such as colleges, hospitals, hotels, and some restaurants, appear to be the most attractive potential markets (see Major 1995 for an excellent set of case studies from around the world). Data on small-scale CHP systems is sparse. The Department of Energy's Energy Information Administration (EIA) does not collect data on systems smaller than 1 MW, and while Edison Electric Institute does collect data, it is not comprehensive (Energetics 1999). As a result, engine sales data and information from institutional small-scale CHP operations were used to estimate current engine-based building CHP (GRI 1998; Pierce 1998; Wadman 1998). One U.S. manufacturer has reported selling more than 600 small, engine-based CHP systems since 1982 (Tecogen 1997). Data for this sector may overestimate the "true" CHP capacity, since they include some standby power systems that operate only intermittently.

Outlook. CHP may soon become economically attractive for small (<1 MW) commercial buildings, and even residential buildings, because of improvements in technologies and smaller customers' concerns that they might face higher prices under retail competition. The small-scale CHP buildings market, sometimes called self-powered buildings, includes systems that generate some or all of their building electricity while providing heating. Some systems produce cooling using engine-driven chillers and new, smaller, highly-efficient absorption chillers. The near-term prospect for total capacity contributed by this segment is modest, considering their small size. However, the long-term prospects for CHP in buildings are more promising. From1988 to 1998, CHP capacity in the U.K. has almost doubled, representing an average growth rate of 9 per cent per annum for the period (CHPA 1998). Government incentives in the U.K. led to the installation of 612 small, engine-based CHP units between 1992 and 1997 (CHPA 1998). If policy in the U.S. follows this example, much progress can be made in this sector. Technological developments, such as more reliable and lower-emitting gas-engine-based packages, as well as a host of new, small-scale applications such as microturbines and fuel cells, are being made. As a result, we project the U.S. small-scale CHP sector could roughly double by 2005. Growth beyond 2010 could be significant if cost and market barriers are addressed. While the barriers previously discussed apply to small-scale systems, installation and operating costs are the most significant for this sector (DOE 1999).

Estimating the Future CHP Potential

The future of CHP depends upon policy developments. If current barriers persist, the net CHP additions will remain modest. If policies remove barriers, significant potential for additions exists. We develop a base case, consistent with existing policies, and a policy case, which assumes barriers have been removed. We then describe our analysis approach as well as the calculations of additional costs and benefits.

CHP Base Case

The CHP baseline, found in the *Annual Energy Outlook 1999*, reports an installed CHP capacity of 51.8 GW in 1997 (EIA 1998). Several other recent reports contribute to an understanding of the CHP baseline in the U.S. One is an assessment of cogeneration in the industrial sector, prepared for the Gas Research Institute (GRI), which reports an installed industrial base of 44 GW in 1995 (EEA 1998). A report on CHP in district energy systems integrates several data sources to provide an estimate of 3.5 GW of additional DES/CHP capacity, for a total CHP baseline of 47.5 GW in 1995 (Spurr 1998). The EIA projects minimal additional cogeneration capacity to be added to the national mix over the coming years: 5 GW by 2010 and 7.3 GW by 2020 (EIA 1998). The GRI projects slightly higher additions, making the EIA's forecasts appear conservative. However, both studies are consistent in that they reflect a deceleration in the market due to previously stated barriers (EEA 1998).

Table 1. Estimates of Potential for Additional CHP Capacity (GW), Relative to 1995

Source	2010	Notes
Base Case Assessments		
Annual Energy Outlook 1999 (EIA 1998)	7.1	Uses extrapolated 1995 capacity
GRI Summary of Industrial Cogeneration Projection (EEA 1998)	10.1	Industry only
Policy Case Assessments		All relative to AEO99 baseline
Scenarios for U.S. Carbon Reduction (DOE 1997b)	27	Industry only
Energy Innovations (Alliance et al. 1997)	30	Industry only
Policies and Measures to Reduce CO_2 Emissions in the U.S. (Bernow et al. 1997)	60	Industry only
DOE/EPA Experts Panel (DOE 1997b)	52	Industry and DES only
District Energy Systems Integrated with Combined Heat and Power District (Spurr 1998)	19	DES only
"The Outlook for Small-scale Combined Heat and Power in the U.S." (Kaarsberg et al. 1998)	20+	Commercial buildings only

CHP Policy Case

A number of recent studies, using varied data sources and approaches, have attempted to define the potential for CHP with barriers removed. Three studies have used the steam generation capacity in the inventory of boilers to estimate additional CHP electric generation potential. These data are combined in the analysis with assumptions on the form of CHP implemented and the economics of operation (Bluestein 1997; DOE 1997a; ICF Kaiser 1997). Another approach, used by three other studies, is based on annual steam generation data. These data were combined with assumptions about the average ratio of electricity to steam production to estimate the additional electric generation capacity; operational assumptions were used to estimate annual electricity generation (Alliance et al. 1997; Bernow et al. 1997; Laitner 1997). Table 1 shows the range of recent base case and policy case projections.

In the fall of 1997, a group of experts from DOE and EPA compared their analyses in order to offer a single estimate of the potential of CHP (see Table 1 above). Using a Delphi approach, the group concluded that doubling CHP over EIA projections of 46 GW by 2010 was achievable with moderate policy reform and outreach (DOE 1997b). They also estimated the technical potential to be at least 160 GW of additional (above EIA) CHP-based electricity generation. The achievable potential to reduce carbon emissions was estimated to be about 30 million metric tons of carbon equivalent (MMT_{CE}), with the technical potential to exceeded 100 MMT (DOE 1997b).

In early 1998, two analyses showed that district energy and small-scale (<1 MW) CHP additions, which had not been included in the DOE/EPA analysis, could be significant by 2010, and major contributors beyond that (Kaarsberg et al. 1998; Spurr 1998). Based on this information, the DOE issued a "CHP Challenge" on December 1, 1998, setting the goal to double CHP capacity by 2010 (DOE 1998). The authors' analyses indicate that this goal is achievable, and, in fact, the most recent estimates indicate that it may be conservative (see Table 1).

In addition to these studies, several other recent evaluations support more aggregate numbers of the technical potential for future manufacturing CHP. These include the previously mentioned OnSite Energy assessments of 36 GW of CHP technical potential in the chemical, food, and pulp and paper industries (1997a, 1997b, 1998). Another analysis used electricity and steam use, boiler vintage, expected retirement data, and assumptions about the electric thermal ratio to estimate a total cost-effective capability of more than 175 GW (Kaarsberg & Roop 1999). A recent preliminary analysis of additional industrial CHP likely to be implemented by 2010 showed a potential of 31 GW (ICF 1999).

Analysis Approach. The base case assessments were combined with projected policy case potentials to obtain estimates of additions from 2000 to 2020 (Table 2). Since most estimates were for 2010 and for industry-only potential, a diffusion curve was fitted to obtain the pre- and post-2010 estimates. Also, no additional new industrial CHP systems were anticipated in the 2000 policy case, since these require three to five years from the time of initial proposal until startup (i.e., 2000 additions are 0). The 2020 figures are roughly 90 percent of the revised economic potential estimates done by the DOE and EPA.

Based on the estimates of capacity expansion (Table 2), we projected energy savings, emissions reductions, and capital expenditures. The industrial figures were based on meta-analysis of available industrial CHP estimates referenced above. We have only one

Table 2. Projections of Additional CHP Capacity in Policy Case

	CHP Capacity (GW)			
Year	**Industrial**	**DES**	**Small-scale**	**Total**
2000	**0**	**0**	**0**	**0**
2005	**17**	**6**	**5**	**28**
2010	**34**	**19**	**20**	**73**
2015	**48**	**34**	**35**	**117**

reference each for the district energy and small-scale CHP calculations (Kaarsberg, et al. 1998; Spurr 1998).

Overall fuel efficiency (OFE), as described in Krause et al.1994, is the ratio of total useful energy outputs to fuel inputs. In our analyses, OFE varies depending on the system configuration. The smallest systems, which use only the highest quality steam, have an OFE rating of 50 percent, while systems with low-grade thermal requirements and/or supplemental firing rate over 90 percent. The OFE also fluctuates as the power-to-heat ratio changes. The power-to-heat ratio indicates the proportion of power (electricity and/or mechanical energy) to heat energy (i.e., steam or chilled water). The most efficient systems have power-to-heat ratios of less than 0.5. We assumed an average OFE of 70 percent and an average power-to-heat ratio of 0.5 in our analysis. This implies an electric efficiency of 23 percent and a thermal efficiency of 47 percent. The net power heat rate of the CHP system is the incremental additional fuel consumed on-site necessary to generate a unit of power, and was assumed to be 4,015 Btu per kWh.

In order to calculate the avoided utility generation, we assumed that the CHP electricity generation capacity is operated at 7,100 hours per year at 90 percent of its rated capacity. This operating profile assumes that the CHP system is sized for the base thermal load of the facility and any excess thermal needs are met by supplemental firing of additional fuel in a boiler. In a restructured electricity market and/or with more advanced CHP technologies, there may be opportunities for a wide range of operating scenarios. Advanced technologies operate at high efficiencies at a variety of power-to-heat ratios and differing applications will meet varying shares of on-site electricity requirements or sell excess generation to the grid based on market electricity pricing. However, the consideration of these scenarios goes beyond the scope of this paper. We assumed that the incremental cost of CHP capacity over that of a conventional boiler to be $650 per installed kW, based on a survey of project costs (Elliott & Spurr 1999). Based on annual utility operating data, we assumed that the displaced utility generation capacity would be 6,000 hours of operation per year at 67 percent of its rated capacity (EIA 1996). The cost of central electricity generation capacity was presumed to be $425 per installed kW.

The net energy savings were calculated using the following expression:

Net savings = (Fossil utility heat rate – Net CHP power heat rate) x Total CHP power

where we used *Annual Energy Outlook 1998* projected fossil-only heat rate for utility generation and the assumed net power heat rate for the CHP system defined above (EIA 1997a). Based on the net energy savings, we calculated the direct economic benefits of the energy savings from the avoided electricity expenditure and additional on-site fuel cost (Elliott & Spurr 1999).

Calculations of Additional Costs and Benefits. We estimated the emissions reductions and investments for industrial and DES/CHP systems only, because insufficient data is available for the small-scale CHP systems. The avoided emissions were determined using the resulting fuel savings above, while emissions factors[1] were derived from EIA data (EIA 1994, 1997b).

Investment costs for CHP are difficult to estimate other than on a case-by-case basis because of the diversity of system configurations, permitting processes, system sizes, inconsistencies in conventions for comparing thermal and electric systems, as well as differences between new sites and the repowering of existing systems. Cost estimates can increase by 25 percent if end-of-pipe emissions controls, such as selective catalytic reduction (SCR) for NO_x, are required (OnSite Sycom 1998). Larger systems (>50 MW), which have lower costs per unit of generation, will average $500 per installed kW. Conversely, the installed cost for smaller systems can easily exceed $1,000 per kW. Since we assume that most of the new capacity, installed by 2005, will be larger systems at industrial facilities, and that the equipment costs for smaller systems are expected to decrease in the future, we use a weighted average cost of $650 per kW, as done in Elliott & Spurr 1999.

Table 3. Energy, Economic, and Environmental Benefits of Additional CHP Capacity*

Year	Addt'l Capacity (GW)	Displaced Generation (TWh)	Addt'l Capital+ ($Billion)	Net Energy Savings (Quads)	Net Savings+ ($Billion)	Carbon Avoided (MMT_{CE})	SO_2+ Avoided (Mt)	NOx+ Avoided (Mt)
2005	28	180	18	1.0	5.3	30	0.6	0.2
2010	73	470	47	2.6	12.0	74	1.4	0.6
2015	117	750	75	3.9	18.0	110	2.2	1.0
2020	152	970	99	4.9	21.0	140	3.0	1.3

*totals may not sum due to rounding
+ does not include small-scale CHP

Conclusion

It is clear from our results that the DOE target of 46 GW of additional CHP capacity is achievable. Our policy case analysis indicates that 73 GW of additional CHP capacity could be achieved by 2010 and 152 GW by 2020. We project that new CHP will result in net energy savings of 2.6 quads and carbon emissions reductions of 74 million metric tons of carbon equivalent (MMT_{CE}) in 2010. Since sufficient data were not available to estimate other benefits for the buildings sector, the industrial and DES systems together would avoid the emissions of 1.4 million tons of SO_2 and 0.6 million tons of NO_x. These systems would require cumulative investments of roughly $47 billion over years. Consequently, CHP could contribute to approximately 15 percent of U.S. Kyoto carbon obligations.

[1] See Emissions Factors (per TWh), Table 10, of Elliot & Spurr 1999.

Despite our technologically moderate projections, these benefits may not be realized because of current and emerging policy barriers that limit widespread use of CHP in the U.S. (Kaarsberg & Elliott 1998). These barriers must be reduced or eliminated so that the U.S. does not bypass a golden economic and environmental opportunity. We can learn from the Europeans—their marketplace experienced similar barriers at the beginning of the 1990's. By providing open electricity markets, moving to output-based environmental permitting standards, and providing exemptions from stranded cost recovery in some countries, they now predict a doubling of CHP's current nine percent share of the EU electricity market by 2010. Similar bold strategies are needed in the United States if the current CHP slowdown is to be reversed.

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