Efficiency Improvements through Combined Heat and Power for On-site Distributed Generation Technologies

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ABSTRACT

With the evolution of electricity market transformation, there is a renewed interest in distributed generation (DG)—that has a promising role for mitigating technical, regulatory, and environmental constraints in the electricity sector. These benefits are further enhanced with the ability of such DG in heat recovery applications in which the waste heat is used to produce hot water, heat building space, drive absorption cooling, and supply other thermal energy needs in a commercial building or industrial process. This article identifies the efficiency gain and other environmental and economical benefits of using fossil fuel based DG under combined heat and power (CHP) application. Based on emission factors and operational performance of existing commercially available DG under both separate heat and power (SHP) and CHP applications, economic and environmental performance of such DG is analyzed and compared under different loading conditions characterized by different heat to power (HPR) ratios.

INTRODUCTION

Gradual changes in the operational and regulatory domains of conventional electric utilities and the rapid emergence of small-scale modular technologies have opened new opportunities and prospects for small-scale on-site power generation. These relatively small–scale distributed generation (DG*) technologies produce energy on a relatively small scale very near to the customer load, either in isolation or connected to an electric network (Turkson and Wohlgemouth, 2001). DG technologies offer an alternative to expensive central generation and transmission line constructions. DG technologies are capable of generating locally controlled power with improved quality and reliability, especially when supplemented with the centralized grid. As a result, the adoption of DG in electricity generation in most of the countries (especially in developed countries including the United States) is increasing. An Electric Power Research Institute (EPRI) study shows that by 2010, DG will contribute nearly 25% of the new future electric generation, while a National Gas Foundation study indicated that it would be around 30% (El-Khattam and Salama, 2004). The CHP systems are more prevalent in European countries than in the U.S. For example, about 50% and 30% of the electricity demands are served by CHP plants in Denmark and The Netherlands, respectively (CEC, 2003; Lund and Anderson, 2005). Based on the enormous success and high penetration level of small-scale CHP applications in these countries, the European Union has a strategic plan to double the CHP based electricity production from 9% in 1994 to 18% in 2010 (Lund and Anderson, 2005).

At present, environmental policies or concerns are probably another major driving force for the adoption of DG. One of the keys to all these benefits of DG technologies is their ability to utilize the waste heat produced as a by-product during the conversion process of primary fuel into electricity. This process is called combined heat and power (CHP). Typically about half to three-quarters of the primary energy consumed in power generation is ultimately unutilized (CEC, 2003). The potential gains from utilizing this heat productively, which would otherwise be wasted from a tail pipe, are significant. Some of the DG technologies, such as gas turbines (GT), reject a high proportion of input energy into exhaust gases, most of which can be recovered (Petchers, 2003). There are three immediately apparent potential applications of CHP in DG technologies: 1) space heating, domestic hot water heating, and sterilization; 2) industrial and manufacturing processes; and 3) space cooling and refrigeration through the use of absorption chilling (CEC, 2003).

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*DG is a new approach in the electricity industry and various literatures have shown that there is no generally accepted definition of DG.

Especially on sites where there is a significant constant demand for heat and cooling, it is worthwhile to consider the CHP option. The primary importance of CHP is the fact that it can increase the system efficiency up to 80% or more in some of the best applications.

This study quantifies the efficiency that can be achieved by operating fossil fuel based DG (i.e., microturbines (MT), internal combustion (IC) engines, and small GT) to meet the on-site electricity and heat demand as well as process. Excess heat from the tail pipes is subsequently used to serve the on-site thermal demand of a facility. Furthermore, this study quantifies emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2), and oxides of nitrogen (NOx) from the total energy supply to a given facility by DG under both CHP and SHP modes. In SHP, electricity demand for a given facility is served by running DG and the heat load is served by burning natural gas in a separate heat boiler. A cost comparison in terms of net present cost (NPC) and average cost of energy (COE) for electricity is made from the operation of DG under both CHP and SHP. Finally, comparison of CHP and SHP is made in terms of environmental emissions over the centralized system. In the centralized system, the electricity demand is served by importing energy from the local electric grid and heat demand is fulfilled by burning natural gas in heat boilers.

DATA SOURCES AND ASSUMPTIONS

In this study, the economic, technical, and environmental characteristics of different DG technologies (i.e., GT, IC engine, and MT) are obtained from the U.S. Environmental Protection Agency (EPA, 2002). GT is available in various sizes ranging from 500 kW to 500 MW, natural gas based ICs in a range of 500 kW to 5 MW, and MT in a range of 30 kW to 350 kW. The total plant cost or installed cost for most CHP technologies consists of the total equipment cost plus installation labor and materials, engineering, project management, and financial carrying costs during the construction period (EPA, 2002). The total installed cost for a typical GT ranges from \$785/kW to \$1,785/kW, while the total installed costs for a typical MT in grid connected CHP technologies ranges anywhere from \$1,339/kW to \$2,516/kW. Commercially available natural gas based spark-ignited IC engine gensets have a total installed cost of \$920/kW to \$1,515/kW (EPA, 2002).

Non-fuel operation and maintenance (O&M) costs typically include routine inspections, scheduled overhauls, preventive maintenance, and operating labor.

For a gas-based IC engine and GT, the O&M costs are comparable. The total O&M cost ranges from $4.2/MWh to $9.6/MWh for a typical gas turbine and from $9.3/MWh to $18.4/MWh for a typical commercially available gas IC engine. Based on the manufacturer service contracts for specialized maintenance, the O&M costs for MT appear to be around $10/MWh. Fuel cost data for heat boilers were taken from Strachan and Farrell (2006) and crosschecked with the EPA CHP technologies catalogue.

The availability rates for an IC engine and GT are estimated to be very high—in the range of 95% and over (EPA, 2002). Given the limited number of MTs currently in commercial use, the reliability figure is difficult to estimate. However, manufacturers of microturbines have targeted availabilities in the range of 98 to 99%. Emission values for DG-CHP units are obtained from EPA.

All costs used in this article are based on the 2000 price. The natural gas price used in the power sector is taken from Strachan and Farrell (2006). The natural gas price is based on $7.70 per thousand cubic feet (mcf) in year 2000 for a commercial facility in New York. This price consists of well head price plus the transmission and distribution costs. The distribution standby service charges, electric supply demand charges, interconnection charge and time-of-use (TOU) kWh used in the analysis are from the tariff schedule of a local power producer applicable to small distribution generation service, Niagara Mohawk Power Corporation, New York (NMPC, 2005).

Electricity Demand and Supply Characteristics

As a case study, a hypothetical commercial facility in the state of New York is assumed due to the availability of data sets. The peak power demand of the facility is assumed to be 600 kW, whereas the off-peak demand is assumed to be 300 kW during weekdays. This makes the average load factor of the system about 43%. The power demand is assumed to be the same throughout different seasons and months, whereas, the thermal load—as a demand for heat energy—is assumed to be highly variable in different seasons. The thermal peak demand is assumed to be equivalent to 1800 kW during the months of November to January, 600 kW during the summer months (May, June, July and

August), and 1200 kW during the months of March, April, September, and October. These power demands for separate power and heat applications are considered to match the heat to power ratio (HPR) values for aggregated seasonal energy demands for New York State. For details about the heat and power demand characteristics of a typical load in New York, the reader is referred to Strachan and Farrell (2006). The HPR of the load is important to address the issue of efficiency variation for different CHP technologies.

METHODOLOGY

HOMER (Hybrid Optimization Model for Electric Renewables) is a micro-power optimization model developed by the National Renewable Energy Laboratory (NREL) in Golden, Colorado (NREL, 2005). The model identifies the least cost DG sets under a given dispatch strategy for satisfying local electricity and heat requirements from different strategic operation of DG. HOMER simulates the operation of a combination of DG by making energy balance calculations for each hour in a year. HOMER performs these energy balance calculations for each system configuration and determines the optimal size and configuration of DG technologies. From various feasible configurations, it calculates the cost of installing and operating DG over the lifetime of the project and displays a list of configurations, sorted by the net present cost (NPC). The project lifetime is the length of time (10 years in this particular study) over which the costs of the system occur.

The model allows one to calculate NPC and cost of energy (COE*) from different combinations of DG technologies. By using the real interest rate, inflation is factored out for the economic analysis in the HOMER model, and all costs, therefore, become real costs. This means all cost figures are expressed in terms of constant dollars for year 2000.

To serve the thermal load with the waste heat, we must specify a non-zero value for each DG's heat recovery ratio (HRR). The heat recovery ratio is a percentage of the heat that can be recovered to serve the thermal load. HOMER assumes that the generator converts a part of the energy content of the fuel into electrical energy, the remaining fuel being converted to heat. HOMER treats the boiler as a backup source

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*The levelized cost of energy (COE) is the average cost of producing electricity.

of heat that can serve any amount of thermal load whenever necessary. Efficiency of natural gas boiler (η_Q) is taken to be 90% per the typical value used in the literature (Strachan and Farrell. 2006).

The model allows us to calculate NPC using the following equation:

$$NPC = \frac{C_{ann,\ total}}{CRF\ (I,\ R_{proj})} \tag{1}$$

Where:

$C_{ann,\ total}$ = total annualized cost (\$/yr)
CRF ( ) = capital recovery factor
I = real interest rate (%)
R_{proj} = project life time (yr)

When DG supply the combined electrical load and the thermal load, the following equation is used to calculate the average total efficiency of a CHP system.

$$\eta_{CHP,\ tot} = 3.6 \quad \frac{E_{gen} + H_{gen}}{m_{fuel} \times LHV_{fuel}} \tag{2}$$

where:

E_{gen} = the total annual electricity production (kWh/yr)
H_{gen} = the generator's total annual thermal production (kWh/yr)
m_{fuel} = the CHP generator's total annual fuel consumption rate (kg/yr)
LHV_{fuel} = the lower heating value of fuel

To calculate the electrical efficiency of a DG in a SHP system using equation (2), the H_{gen} term in the numerator becomes zero. Similarly, for the efficiency estimation of a separate boiler system for heating purpose only, the E_{gen} term will become zero. The total fuel consumption rate m_{fuel} is obtained from a fuel curve (specified) for a given DG technology. The fuel curve describes the amount of fuel the generator consumes to produce electricity, and is considered a straight line in this HOMER model.

The primary fuel savings (PFS) potential of a DG-CHP system compared to SHP is given by the following equation (Pepermans et al., 2004).

$$PFS = (\frac{\alpha_E}{\eta_E} + \frac{\alpha_Q}{\eta_Q} - 1)m_{fuel} \tag{3}$$

where,

α_E= electrical efficiency of CHP system
α_Q=thermal efficiency of CHP system
η_E= electrical efficiency of SHP system
η_Q=thermal efficiency of SHP system

The EC (i.e., the emission coefficient) of the DG technologies (gas turbine, IC engine, or microturbine) of a per unit primary input energy is given as:

$$EC = \frac{Amount\ emitted\ in\ (kg/yr)}{Primary\ fuel\ input\ (J/yr)} \tag{4}$$

Equations (2) and (3) give annual avoided emissions from a CHP system compared to a SHP as:

$$Avoided\ emissions = \left(\frac{\alpha_E}{\eta_E} + \frac{\alpha_Q}{\eta_Q} - 1\right)EC \tag{5}$$

RESULTS AND DISCUSSIONS

Optimal Mix of DG

Mainly the design and planning aspects of DG will be discussed in this section for a given heat and electric load of the given facility in New York: the type, size and numbers of DG under both CHP and SHP modes. Optimum sizes and numbers of DG, amounts of heat and electricity produced, and the amounts of primary fuel required by each DG technology will give the information on how much efficiency can be achieved using the waste heat under the CHP mode (see Equation 2). Considering New York as an area where the intended DG will be installed, what will be the implications on the environmental performance of CHP and SHP compared to the centralized system.

Under the SHP mode, the optimal capacities of DG are one unit of 500 kW sized IC engine and one unit of 350 kW sized MT. Despite the high capital cost of MT compared to IC engine and GT, MT is selected to match the electrical load. IC engine contributes about 91% of the annual electricity requirements for a given facility, and 9% is contributed by MT. A natural-gas-fired heat boiler satisfies the entire on-site heat requirement by producing about 6.0 million kWh equivalent of thermal energy during a year. This heat corresponds to about 0.68 million m^3 of natural gas as the primary energy. MT and IC engines together consume about 1.01 million m^3 of natural gas annually to meet the electrical load. The average seasonal thermal load during the summer is about half of the corresponding load of the winter. The yearly average HPR is about 1.76 for the given facility. Under this mode, MT and IC engines have an average electrical efficiency of 30% and 29%, respectively. The initial capital requirement for the given project during the project lifetime (next 10 years) is $4.53 million with an average COE of $0.158/kWh.

Under the CHP system, IC engine and GT with one unit each (500 kW) are optimal DG capacities. Higher capacities of DG requirements in this case are due to the energy requirement for both primary electrical and heating loads for a given facility. About 70% of the annual electrical energy is contributed by a GT and an IC engine contributes 30%. Whereas, GT serves 59% of the thermal energy, and IC engine and heat boilers serve about 20% and 21% of the heat energy requirements, respectively. Note that the heat energy served from DG sources is dependent upon the heat recovery ratio (HRR). HRR is assumed to be 60% in this case. Altogether, 0.17 and 1.24 millionm^3 of natural gas is required annually for the heat boiler and DG, respectively, to serve the combined heating and electrical load for the given facility. On-site DG can supply the entire heating load requirements during the entire summer due to lower heat requirements. When GT and IC engines operate under the CHP mode, the total system efficiency reaches to 71.3% as opposed to 29% (electrical) under the SHP mode. The initial capital requirement for the given project over the entire project life is $3.93 million with an average COE of $0.130/kWh.

Economic and Environmental Benefits of CHP

The results of this study show that the potential benefits of an increased conversion efficiency under CHP mode are multifold. There is a significant reduction in primary energy demand for satisfying the same level of electrical and heating load when operated under the CHP mode. Compared to the SHP application, CHP results in reducing natural gas consumption by about 14%. This results in an annual savings of

$70,810. This primarily will help to reduce NPC and COE by about 13% and 18%, respectively, over the SHP system.

Environmental emissions depend on the carbon content of the fuel and the conversion efficiency of electricity and the heat supply system. The gain in efficiency due to the CHP results in significant reductions in CO_2, SO_2, HCs, PM, SOx, and NOx emissions. CHP results in the reduction of these environmental pollutants by about 13 to 18%. These results clearly demonstrate that for efforts to abate environmental emissions as part of policies to respond to global climate change problems, DG-CHP technologies offer a promising option. This option—clearly—is a no-regret option, which is environmentally friendly, and at the same time, economically attractive. Significant emissions reduction can be achieved without extra investment in such technologies.

Efficiency Gain under Different Heat to Power Ratio

Various studies indicate that for any technology or combination of technologies, the total CHP efficiency will vary depending on size and HPR of the energy supply system and the load. At the facility level, there is a considerable variability in HPR, and one of the ways to achieve a higher efficiency for a supply system (DG technology) is to design a system with rapidly variable HPR ratio to match the variable load (Colella, 2005; Strachan and Farrell, 2006). Based upon this fact, we try to correlate the total system efficiency of CHP systems with the HPR of DG and the load, obtained from our simulation studies.

The results illustrate that the monthly average HPR of the load in the facility varies from 1.0 in the summer (June) to 2.61 in the winter (January), whereas HPR of the supply system varies from 1.61 to 1.65, which is relatively lower than the HPR of the load. Though the pattern of variation of HPR of the supply system more or less matches the variation pattern of the load, the average monthly HPR ratio of the supply system is always less than the monthly average HPR of load. This is because the heat recovered from the exhaust system is not adequate to serve the heat load of the facility at this level of heat recovery. For this mismatch (magnitude wise) of HPRs of supply system and load, the total system efficiency is about 71.3%. This efficiency gain can be significantly improved with the increase of HPR of the supply system, which can be increased by increasing the heat recovery ratio of the supply system. Higher HPR leads to a higher fuel efficiency resulting in lower emissions. This is because heat conversion process is more efficient than electrical conversion. Moreover, a variable HPR enables a power plant to achieve both reliability and flexibility. Reliability and flexibility are two of the most important characteristics for power generators in the emerging liberalized electricity markets (Colella, 2002). But matching the HPR demanded from a local facility with the supply from a small-scale CHP system is a formidable task (Colella, 2002). This is because the heat and power demanded in a home or an office complex varies so rapidly and sporadically over a large range. For example, if a lighting load varies between 0.3 kW base load to 9.0 kW peak (in a fraction of second) assuming that the heating load is constant, the value of HPR varies by a factor of at least 30.

Comparison of DG-CHP over the Centralized System

In this section, we compare the economic and environmental performance as a result of DG operation under the CHP mode over the centralized system. When DG based MT, IC, and GT are operated in parallel to the macrogrid under the CHP and SHP modes, these DG are no more economically attractive without any policy or market intervention from the government. This means that the centralized system is the least cost option for supplying the given facility under the desired reliability index of the macrogrid. Operations of DG under the CHP system results in SO_2 emissions reduction by about 25% compared to the existing case; however, this results in an increase of more than 28% of NPC and more than 50% of the average electricity price. The lower SO_2 emissions under CHP mode is due to low sulfur content in the fuel (natural gas). NO_X emission under the CHP system is double that of the centralized system. Even if the average NOx emission factor for both GT and IC engine is lower than the average emission factor for a New York grid, higher NOx emission from DG in the CHP mode is due to higher amounts of natural gas used compared to the centralized system. In the centralized system, natural gas is used only in heat boilers to serve the heating load of the facility. In terms of CO_2 emissions, both technologies are indifferent.

Sensitivity Analysis

One of the keys to the success of CHP is its ability to capture its wasted heat and utilize it in serving the thermal load. The simulation model assumes that the remaining fuel energy—after supplying the electric load by DG generators—gets converted to heat. The effective use of

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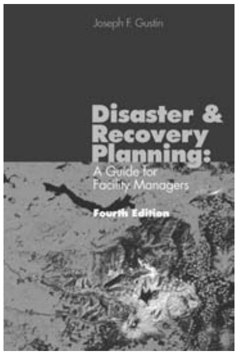

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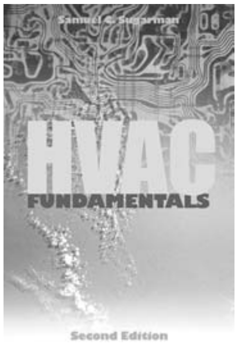

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the thermal energy contained in the exhaust gas improves the efficiency of the CHP system. Recuperators are commonly used heat exchangers that use the heat content of the hot exhaust gas for heating or cooling loads. It is impossible to transform the waste heat into useful energy. Heat exchangers can capture about 80% of the heat from the exhaust gas (USEPA, 2002). The overall efficiency of the CHP system depends upon the performance of recuperators—recuperators can more than double the DG efficiency depending on the DG operating parameters, such as ambient conditions (pressure, temperature, and altitude). Hence, it is interesting to see the performance of DG under CHP applications with respect to variable HPR of the supply system, which can be changed with an increase of the HRR from the exhaust gas. Increasing the HRR of DG technologies basically increases the capacity of heat that can be recovered and subsequently utilized from the exhaust gas.

When HRR is increased from 20% to 80%, this results in an increase of average monthly HPR of the supply system from 0.49 to 2.18. Operating DG under high HPR will result in higher HPR matching the high HPR of the load, increasing the efficiency of a CHP system. This is because the greater the amount of energy recovered from the exhaust gas, the higher the system efficiency will be and lower the primary energy requirement will be. Efficiency gain as high as 86% can be achieved by increasing the average yearly HPR of the supply system to 2.18 at the HRR of 80%, at which the monthly average HPR of the load is about 1.76 (see Figure 1). This result parallels the result of CEC (2003). This efficiency gain—from 44% to 86%—results in the reduction of average cost of electricity (i.e., COE) by about 21%. The gain in average cost of electricity is comparatively low because there is not a significant increase in electrical efficiency. Because the heat boiler remains on standby to supply the balance of the thermal load, the HPR of the CHP system is not limited on the low end because thermal energy can always be generated using the heat boiler even if the CHP system is serving a lower percentage of the thermal load at low HRR. Increasing HRR continues to reduce the natural gas requirements to be used in the heat boiler to serve the thermal load. Operating DG at 80% HRR, only about 9% of the thermal energy needs are served by burning natural gas in the heat boiler (see Figure 1).

Another important reason for operating DG at a higher HPR is the environmental restrictions. It can also be illustrated that the break-even average annual HPR of the supply system is 1.3, which is a trade-

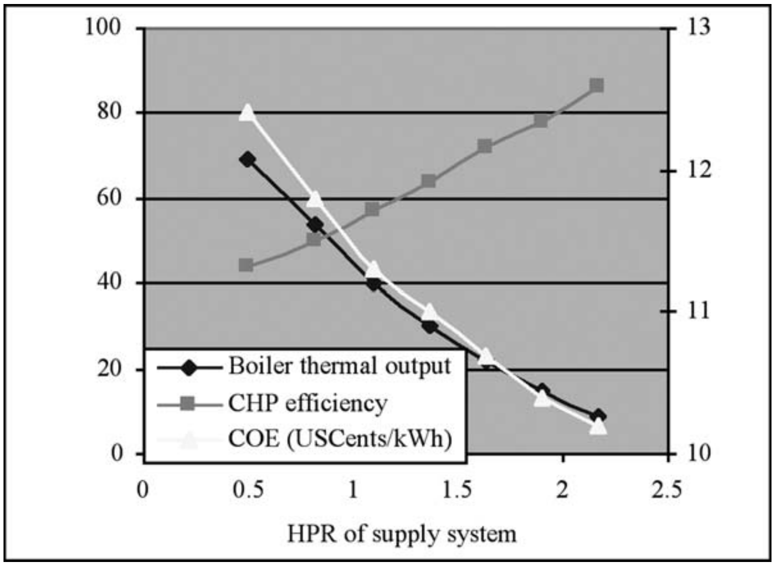

Figure 1. Performance Variation of DG-CHP with HPR

off that makes the DG-CHP system environmentally friendly (in terms of CO_2 emissions) compared to the centralized system. This is why the US EPA proposed regulations for industrial CHP set a minimum HPR value for all DG-CHP technologies (Strachan and Farrell, 2006). The HPR implied by the California Air Resource Board's CHP credit calculation varies from technology to technology because the definition of CHP is based on the system efficiency. Thus, the minimum amount of recovered heat needed to attain the standard varies, and so does the minimum HPR to meet the definition of CHP.

CONCLUSIONS AND FINAL REMARKS

In this article, the environmental, technical, and economic efficiency gains from using fossil-fuel based DG under CHP applications are studied and assessed. Under the CHP system, IC and GT engines are the technologies selected to serve the electrical and thermal load of a typical commercial facility in New York. The results illustrate that efficiency gains from DG-CHP are highly dependent on heat to power ratio of the supply system. Operating DG-CHP in a variable HPR with its ability to respond as per the HPR variation of load is highly desirable for achieving high efficiency gains. From the environmental regulation point of view, it is also important to operate a DG-CHP at a minimum HPR ratio such that the local air quality is better than the centralized system. Because the environmental emissions and cost-economics are two critical factors for the fossil-fuel based DG technologies in the U.S., the CHP system can contribute to transformation of the United State's energy future through an economy-wide energy efficiency improvement and emissions reduction.

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