Climate Change-Driven Market Opportunities for Combined-Cycle Gas Turbines

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Steven H. Ramsey

Trinity Consultants, 1360 Post Oak Boulevard, Suite 1550, Houston, TX 77056

ABSTRACT

Combined-cycle gas turbine cogeneration technology is currently enjoying wide popularity due to a variety of technological, environmental, and financial performance advantages relative to other technologies, specifically boilers. While the environmental performance advantages of this technology have focused on emissions of regulated air pollutants, such as sulfur oxides and nitrogen oxides, cogeneration also provides superior performance with regard to emissions of greenhouse gases. For the case presented within this paper, application of combined-cycle gas turbines demonstrates a 65% reduction in carbon dioxide emissions relative to traditional methods of generating electricity and steam for industrial use. While no regulatory program currently mandates reductions in emissions of greenhouse gases, the emission reductions do have value and can be traded as a commodity. Failure to account for this value may result in an incomplete financial feasibility analysis when assessing options for either replacement or new capacity applications. As more companies move toward full environmental cost accounting, specifically inclusion of costs associated with emissions of greenhouse gases, there should be even more opportunities for the application of combined-cycle gas turbine cogeneration technology.

INTRODUCTION

Currently, combined-cycle gas turbines are a very popular technology. This popularity stems from the many financial and technological advantages associated with the application of turbines in cogeneration systems – defined as the generation of electricity and high-pressure steam for use in industrial applications – such as:

- Revenue from long-term contracts to sell steam and electricity to the host site(s) as well as revenue from the sale of excess electricity on the open market, often at peak-use rates;
- The speed at which turbines can be permitted and installed, relative to traditional power boilers;
- Adaptability of turbines to a very wide range of capacities, ideal for distributed power applications;
- Design flexibility with regard to additional electricity generation via steam turbines and steam generation through installation and application of duct burners; and
- High operating efficiencies and relatively low operating costs.

In addition, combined-cycle gas turbines also provide significant environmental performance advantages relative to coal-fired boilers. With regard to air quality impacts, these advantages include low emissions of particulate matter, sulfur oxides, volatile organic compounds, and hazardous organic and inorganic compounds. Of course, this is typical of any sweet natural gas-fired combustion system. Turbines can also achieve very low levels of nitrogen oxides (NO_X) emissions. Turbines without flue gas treatment have been able to consistently demonstrate NO_X emissions of 9 parts per million by volume (ppmv) and less. Turbines with post-combustion application of selective catalytic reduction (SCR) have demonstrated NO_X emissions of less than 3 ppmv.

This large set of performance advantages associated with combined-cycle gas turbines has resulted in this technology dominating the new steam and electricity generating market in the Houston-Galveston, Texas, area. Beyond just new capacity, many industrial operations are also evaluating or implementing projects to replace existing steam boilers with cogeneration systems.

In the Houston-Galveston Area, the dominant environmental consideration in evaluating technologies for new capacity and/or replacement technology is the associated NO_X emissions. This makes sense considering that the recently adopted changes to the State Implementation Plan mandate an 85% reduction in overall area NO_X emissions from industry by April 1, 2007 (relative to 1997 baseline emissions). The magnitude of the required reductions is forcing industrial operators to evaluate all of their emission sources, including boilers used for steam and/or electricity generation. The options available to reduce NO_X emissions associated with these sources include the following.

- Retrofitting boilers with advanced combustion technology and/or flue gas treatment systems (such as SCR).
- Replacing boilers with a different technology – turbines.
- Shutting down boilers and purchasing steam and electricity from a third-party.

An additional environmental benefit associated with the application of combined-cycle gas turbines, but one seldom considered in the decisionmaking process, is with regard to emissions of one or more of the greenhouse gases: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. For combustion processes, the greenhouse gas of interest is carbon dioxide, CO_2. Turbines emit fewer greenhouse gases than the traditional combination of boilers used to generate an equal quantity of electricity and steam. While, in the opinion of the author, exclusion of these benefits results in an incomplete financial and environmental performance analysis, there are a number of reasons why companies are ignoring greenhouse gas emissions when they evaluate new technologies.

- Emissions of greenhouse gases are not currently regulated.
- There are no programs in place that provide financial incentives for investing in technologies that emit lower quantities of greenhouse gases.
- There are no guarantees that future regulatory and/or financial incentive programs will provide for crediting reductions that occurred before the date of the program (referred to as *early action credit*).

- The markets have not matured sufficiently to establish a firm value for early action credits.
- There is continuing debate over who owns emission credits resulting from reduced demand for electricity from utilities. Does the utility own the credit or does the company that took the action that resulted in the reduced demand own the credit?

Without answers to these questions, it is often difficult to convince business managers and/or accountants to incorporate greenhouse gas emissions into the project feasibility studies. Regardless, failure to consider greenhouse gas emissions results in an incomplete financial and environmental performance analysis, potentially impacting the project decisionmaking process.

OVERVIEW OF GLOBAL CLIMATE CHANGE POLICY DEVELOPMENTS

Over the last decade there have been consistent reports in the media about climate change purportedly linked to human activity. Within the political community, debate continues to rage about:

1. Whether or not the earth's climate is, in fact, changing;
2. If it is, whether or not that change is resulting from human activity, specifically the emission of so-called greenhouse gases; and
3. Whether or not government action should be taken to regulate emissions and/or provide financial incentives for voluntary reductions in emission of greenhouse gases.

Interestingly, the scientific community is much more unified on this issue. The Intergovernmental Panel on Climate Change (IPCC) has taken the position that global warming is real and that recent changes in the climate of the planet cannot be explained by natural phenomena alone. Other respected scientific organizations, such as the Union of Concerned Scientists and the National Academy of Sciences' National Research Council, have also adopted positions that human-enhanced global warming is a real and observed phenomenon. As excerpted from the IPCC's *Second Assessment Report*: "the balance of evidence suggests that there is a discernible human influence on global climate change."[1]

In light of the evidence of human contributions to global climate change, the international community – through the Kyoto Protocol – has taken a small but real and significant step toward reducing emissions of pollutants that contribute to global warming. However, this is only a small first step. It is now generally believed that in order to stabilize atmospheric concentrations at levels 50% greater than those experienced today, emissions of greenhouse gases will need to be reduced over the next 50-100 years approximately 50% worldwide from 1990 emission levels. The Kyoto Protocol only requires a 5.2% reduction in emissions from developed countries and it excludes developing countries (including the world's most populous countries, China and India) from this initial effort.

The future of the Kyoto Protocol is very much in question. As demonstrated at the most recent meeting of the Conference of the Parties in The Hague, Netherlands, in November 2000 (COP-6), significant disagreements exist between the industrialized nations on implementation of the protocol. The Umbrella Group, led by the United States, insists on unrestricted access to flexible mechanisms for implementation – such as Joint Implementation, Clean Development Mechanism, emissions trading, and carbon sequestration. The nations of the European Union continue to insist on limiting the use of flexible implementation mechanisms. Even if these disagreements are resolved, it remains unlikely that the U.S. Senate will ratify the treaty in the near future. Nevertheless, even staunch political opponents of the Kyoto Protocol are discussing the merits of various programs providing for investments in cleaner technologies and financial incentives for voluntary actions.

EMISSIONS OF GREENHOUSE GASES FROM TURBINES

Combined-cycle gas turbine technology has a number of advantages, with respect to greenhouse gas emissions, over more traditional power and steam generation systems, specifically boilers. These advantages are associated with system design and use of natural gas as the fuel.

- *The design of combined-cycle gas turbines allows much higher overall system efficiencies* than conventional power and steam boiler combinations. Overall cogeneration system efficiencies can exceed 80 percent (conversion of chemical energy in the fuel to electrical energy and heat energy in the steam).[2] Typical power boilers only achieve efficiencies of 30-35 percent. A typical steam boiler will operate at efficiency in excess of 60%. Consequently, for the same amount of fuel consumption, and thus greenhouse gas emissions, cogeneration systems generate more output.

- *Natural gas is a cleaner burning fuel* than either oil or coal. With regard to greenhouse gas emissions, natural gas has greater energy density relative to fuel carbon than other fossil fuels – coal and oil. Therefore, per unit of heat input there are less emissions of carbon dioxide. Table 1 presents relevant fossil fuel properties.

Table 1. Fossil Fuel Properties

Fuel		Average Heat Value	Average Carbon Content (%)	Average Heat Value (Btu/lb Carbon)
Coal	*Anthracite*	13,700 Btu/lb	84	16,300
	Bituminous	14,300 Btu/lb	80	17,900
	Subbituminous	9,400 Btu/lb	55	17,100
	Lignite	7,200 Btu/lb	42	17,100
Oil	*No. 2*	141,000 Btu/gal	86	22,700
	No. 4	146,000 Btu/gal	86	21,900
	No. 6	150,000 Btu/gal	86	21,900
Natural Gas		1,000 Btu/ft^3	75	32,000

Data derived from *Air Pollution Engineering Manual*.[3]

When assessing environmental impacts, both direct and indirect, associated with a technology, the analysis should address total life cycle impacts. For power and steam generation systems these would include impacts associated with fuel extraction, processing, transportation and storage on the upstream side and waste generation, transportation, and disposal on the downstream side. Intuitively, we expect life-cycle impacts associated with natural gas use to be less than the impacts associated with either oil or coal. Currently, most companies do not account for life-cycle environmental impacts that are not under their direct control.

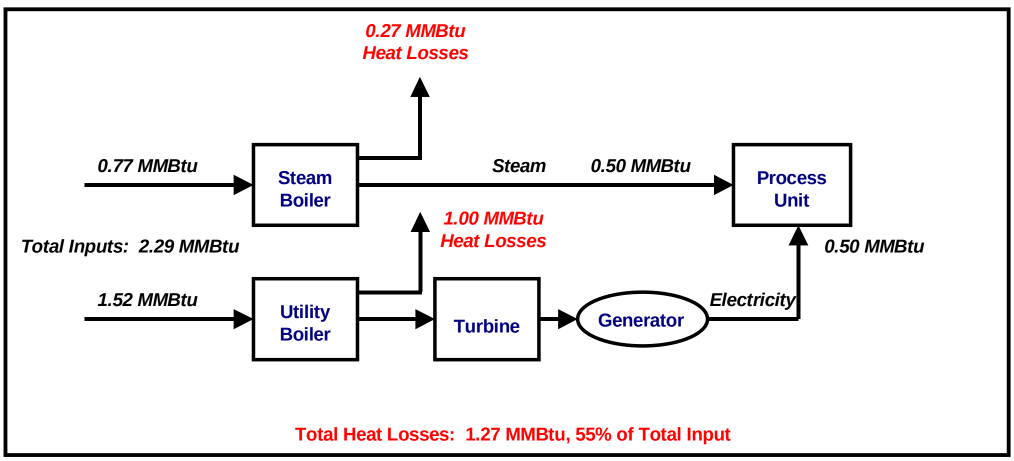
COMPARATIVE GREENHOUSE GAS EMISSION PROFILES

In comparing emission profiles, combined-cycle gas turbines are compared to the most common sources of electricity and steam currently consumed in an industrial facility. Industrial facilities typically purchase electricity from the grid and generate steam on-site. In Southeast Texas, the utilities utilize large coal-fired boilers as base-load units, with smaller natural gas-fired boilers and turbines as peaking units. The comparison assumes electricity generation in the coal-fired units. With regard to on-site steam, the great majority is generated in natural gas-fired boilers – excepting, of course, industrial sites that already utilize combined-cycle gas turbines.

Traditional Power & Steam Generating Systems

Figure 1 graphically presents an energy balance for the delivery of 1.0 MMBtu of energy to a process unit – 50% as electricity and 50% as heat in the form of steam.

Figure 1. Energy Balance for Traditional Power & Steam Generating Systems



The assumptions used in preparing the energy balance are as follows.

- The power boiler is 33% efficient at converting fuel energy into electrical energy
- The steam boiler is 65% efficient at converting fuel energy into heat energy in the form of steam

With these assumptions, the traditional power and steam generating system is approximately 45% efficient overall. Fifty-five percent of the input energy is lost as unrecovered heat.

Assuming that the utility boiler is fired with subbituminous coal, a calculation of greenhouse gas emissions – carbon dioxide (CO_2) – per unit of output can be made for the system. Emissions associated with coal combustion are estimated as follows.

Eq. 1. $$E_{CO_2} = \frac{\left[(44\,lbs\,CO_2 / 12\,lb\,Carbon) \bullet (0.55\;lb\,Carbon / 1\,lb\,Coal)\right]}{\left[(9{,}400\,Btu / lb\,Coal) \bullet (1\,MMBtu / 10^{+6}\;Btu)\right]} = \frac{214.5\,lbs\;CO_2}{MMBtu}$$

For the scenario presented in Figure 1 (1.52 MMBtu input to the coal-fired utility boiler), CO_2 emissions associated with coal combustion are estimated as 326 lbs.

Emissions associated with natural gas (assumed to be 100% methane) combustion in the steam boiler are estimated using the following equation.

Eq. 2. $$E_{CO_2} = \dot{n} \bullet \left[(44\,lbs\,CO_2 / 12\,lbs\,Carbon) \bullet (0.75\,lb\,Carbon / 1\,lb\,CH_4) \bullet (16\,lb\,CH_4 / 1\;lbmole\,CH_4)\right]$$

Where $\dot{n}$ is the molar flowrate of natural gas per MMBtu calculated using the Ideal Gas Law.

Eq. 3. $$PQ = \dot{n}RT, \text{ where:}$$

P = absolute pressure (atm)
Q = flowrate (ft^3/MMBtu)
$\dot{n}$ = lbmoles/MMBtu
R = Gas Constant (1.314 atm•ft^3/lbmole•°K)
T = Absolute Temperature (°K)

Substituting and solving Equation 3 for one atmosphere pressure, 20°C and 1,000 ft^3/MMBtu.

Eq. 4. $$\dot{n} = \frac{\left[(1\,atm) \bullet (1{,}000\;ft^3 / MMBtu)\right]}{\left[(1.314\,atm \bullet ft^3 / lbmole \bullet {}^\circ K) \bullet (293^\circ K)\right]} = \frac{2.6\,lbmole}{MMBtu}$$

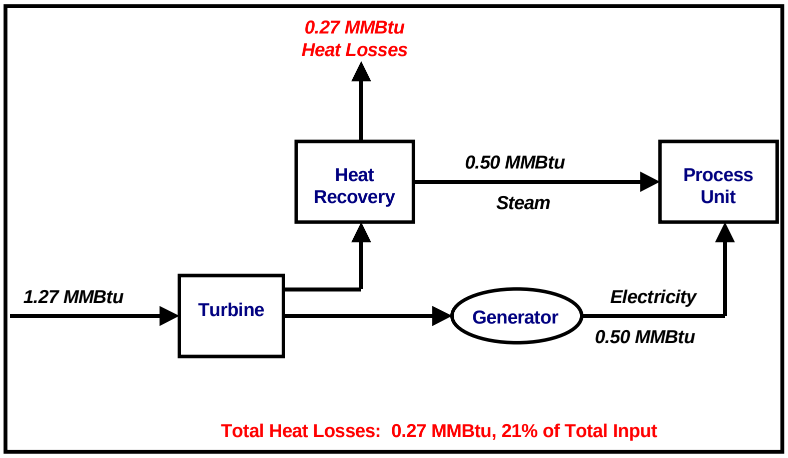
Solving Equation 2, CO_2 emissions are estimated as 114.3 lbs/MMBtu. For the scenario presented in Figure 1 (0.77 MMBtu input to the natural gas-fired steam boiler), CO_2 emissions associated with natural gas combustion are estimated as 88 lbs. Total emissions associated with the scenario presented in Figure 1 are the sum of the CO_2 emissions associated with natural gas and coal combustion. This total is 414 pounds.

Cogeneration Systems

Figure 2 graphically presents an energy balance for the delivery of 1.0 MMBtu of energy to a process unit – 50% as electricity and 50% as heat in the form of steam – from a combined-cycle gas turbine cogeneration system. The energy balance assumes 100 percent efficiency in generating electricity and 65 percent efficiency in generating steam for an overall system efficiency of 79%.

Applying Equation 2 to the scenario presented in Figure 2 (1.27 MMBtu input), CO_2 emissions are estimated as 145 lbs.

Figure 2. Energy Balance for a Combined-Cycle Gas Turbine Cogeneration System



Relative Performance

CO_2 emissions associated with the presented cogeneration system is 35% of emissions associated with the presented traditional power/steam generating system. Put another way, replacing traditional power and steam generation with cogeneration can result in a 65% reduction in emissions of greenhouse gases.

ACCOUNTING FOR SUPERIOR GHG EMISSION PERFORMANCE

The superior performance of cogeneration with respect to emissions of greenhouse gases is clearly evident. Now for the hard question, what *value* should be assigned to this relative performance advantage? As stated, emissions of greenhouse gases are not currently regulated in the United States. Trading of greenhouse gas emissions is a fledgling industry, exclusively the domain of:

1. Companies that have established internal emission trading programs, and
2. Companies that are trading options as a hedge against future mandated market-based programs.

Per discussions between the author and Ms. Ann Egleston with Evolution Markets (telephone number 212.430.6475) on January 29, 2001, options are currently trading between $0.75 and $5 per metric ton CO_2 equivalent. For emission reductions at U.S. facilities associated with fuel switching or efficiency enhancements that are verifiable, a price of $1 to $2 per metric ton CO_2 equivalent is the best estimate of the current range of trades.

Future prices may be considerably higher if the Kyoto Protocol is ever passed into law or if an alternative program takes affect. Many technology feasibility assessments have assumed pricing in the $20 per ton CO_2 equivalent range. However, experience with NO_X and SO_2 has shown that market-based emission reduction programs are very effective at reducing compliance costs. Prior to implementation of the acid deposition control program (Title IV of the 1990 Clean Air

Act Amendments), the U.S. EPA estimated that SO_2 would trade close to $2,000 per ton. However, credits have consistently traded at less than $200 per ton.

EXAMPLE: 250 MW COGENERATION PLANT

A new 250 megawatt (MW) capacity natural gas-fired combined-cycle gas turbine cogeneration plant is to be installed adjacent to a petrochemical host site. On average, 50% of the cogeneration plant's output will be in the form of electricity, 50% in the form of steam that is sold to the host. The new plant will replace existing steam boilers and will eliminate the need to purchase electricity from the grid – resulting in reduced electricity demand from existing coal-fired utility boilers. Following is a performance summary with regard to emissions of greenhouse gases.

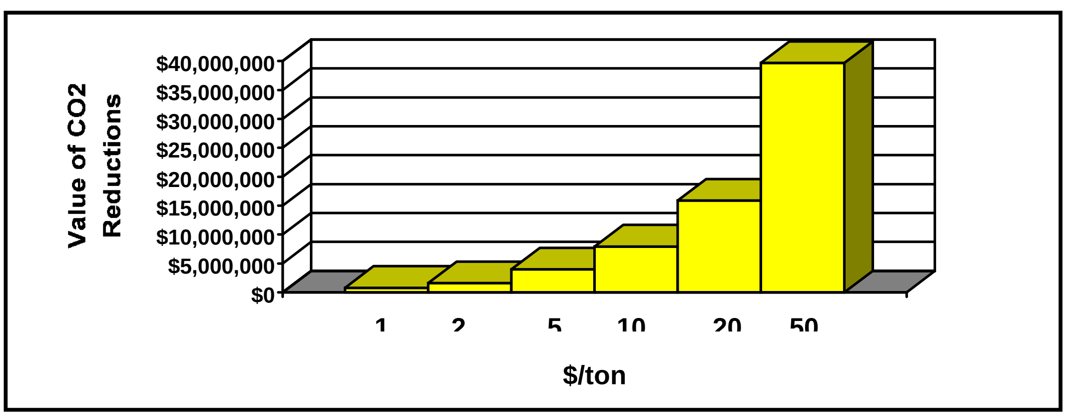
- Assuming 100% utilization of the new plant at 100% capacity, annual CO_2 emissions are calculated using Equation 5. As shown in Equation 4, $\dot{n}$ is 2.6 lbmole/MMBtu for 1,000 Btu/ft^3 natural gas (1 atm., 20°C). Solving, CO_2 emissions are approximately 427,400 tons per year.

Eq. 5. $E_{CO_2} = \dot{n} \bullet [(3.412\,MMBtu/hr)/(1\,MW)] \bullet (250\,MW) \bullet (8{,}760\,hrs/year) \bullet (44\,lbs\,CO_2/lbmole) \bullet (1\,ton/2000\,lbs)$

- Utilizing the greenhouse gas emission ratio previously presented— cogeneration emissions at 35% of emissions associated with traditional power and steam generation systems – the proposed plant will replace approximately 1,221,100 tons per year of CO_2 emissions.
- The net emissions reduction associated with the project is approximately 793,700 tons per year of CO_2.

Figure 3 graphically presents the value associated with these reductions at various dollar-per-ton rates ranging from $1 to $50 per ton.

Figure 3. Value of CO_2 Emission Reductions as a Function of Unit Pricing for the 250 MW Cogeneration Plant Example



The values presented assume contractual ownership of the credits resulting from emission reductions at the utility.

Even under the high cost scenario, the market value of the greenhouse gas emission reductions is not large relative to the capital cost of a new cogeneration plant – approximately $200 million for a 250 MW facility. However, the value of these emission reductions may affect project feasibility or, at a minimum, make the project more financially attractive. Regardless of the impact on the decisionmaking process, as shown in this example, failure to fully account for greenhouse gas emissions associated with the project will result in an incomplete analysis, potentially an omission of significant magnitude.

CONCLUSIONS

The intent of this analysis is to demonstrate that:

1. Combined-cycle gas turbines provide superior performance with respect to emissions of greenhouse gases, specifically CO_2, when compared to more traditional electricity and steam generating systems;
2. The emission reductions do have a market value, even though there is no current regulatory program mandating those emission reductions; and
3. The value of these reductions should be taken into consideration when evaluating the environmental advantages and financial feasibility of a new cogeneration project.

As the policy developments progress and a market for greenhouse gas emission credits fully develops, there should be even more opportunities for the application of this already popular technology.

REFERENCES

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KEY WORDS

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Cogeneration
Combined cycle
Emissions trading
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