

# Using and Measuring the Combined Heat and Power Advantage

[Tommy John](#) PE, *Tommy John Engineering, Inc.*

American Institute of Chemical Engineers, Spring National Meeting 2010

## Abstract

Combined Heat and Power (CHP), also known as cogeneration, refers to the integration of thermal energy with power generation. CHP is a powerful energy conservation measure that has been identified as an important greenhouse gas reduction measure with net economic benefits. It complements other energy conservation measures. CHP can be used any place that heat is needed so it is used with a variety of applications, fuels, and equipment. There are ancillary benefits of CHP to the host site and the public including air quality, reliability, reduced water consumption, and economic development.

There is sometimes confusing information about the benefits of CHP because there is no universal standard for reporting the efficiency of CHP systems. This results in both overstatement and understatement of the benefits of CHP compared to other power generation systems. Fuel Charged to Power (FCP) is the fuel, net of credit for thermal output, required to produce a kilowatt-hour of electricity. This provides a metric that is used for comparison to the heat rate of other types of generation and insight into the development of CHP projects that maximize economic and environmental benefits.

Biomass generation is generally less efficient than fossil fuel generation due to size and combustion characteristics, which means that there is more benefit from CHP because there is more waste heat available for recovery. An example is presented demonstrating that CHP significantly improves the economics and environmental benefits for biomass to power.

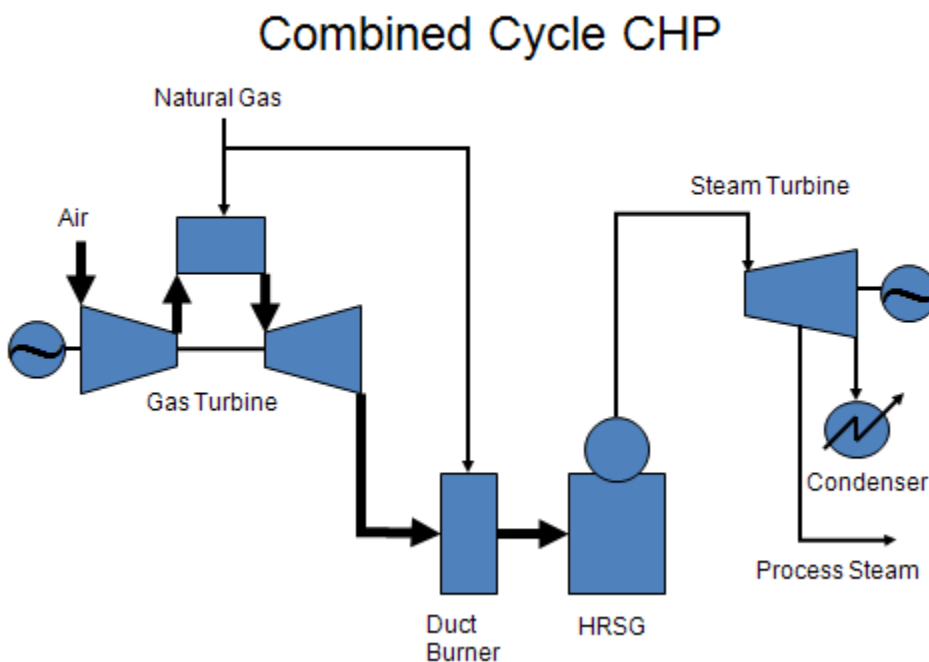
## Combined Heat and Power

Combined Heat and Power (CHP), also known as cogeneration, refers to the integration of thermal energy with power generation. CHP plants are a major energy conservation technique because they are 70% to 90% efficient compared to a modern natural gas combined cycle power plant that operates at about 50% efficiency. CHP is an important greenhouse gas reduction measure that has net economic benefits. Shortage and higher costs of energy resources and the need to mitigate environmental impact make CHP a viable resource even though the plants are usually smaller and more complex. CHP can be used any place that heat is needed. The systems can be very large to serve the thermal load at a petroleum refinery or petrochemical complex, or small to match the heat load of a building, hospital, university campus, or school.

CHP currently provides about 8% of the power generated in the US, but there is potential for much more. Increased implementation of effective CHP will benefit not only the host site, but all energy consumers and the public with dramatic energy efficiency and air quality benefits in addition to improving the reliability of energy supply, reducing load on the transmission and distribution system, reducing water consumption, spurring economic development, and meeting potential carbon reduction requirements.

## CHP Systems

CHP can use any fuel type; natural gas, biofuels, byproducts of agriculture and manufacturing, waste heat from manufacturing processes, and methane gas produced from landfills and anaerobic digesters. A variety of proven, reliable technologies are available to match any application including internal combustion engines, combustion turbines, steam turbines, and heat recovery systems. The most common fuel is natural gas. The following figure shows a natural gas combined cycle CHP plant. This arrangement, which often includes multiple gas turbines, provides the operator with maximum flexibility to supply thermal energy and optimize supply to the electric grid. Many plants include only some of the elements shown; for example a gas turbine and heat recovery steam generator (HRSG) only, or a boiler and back pressure steam turbine.



## Energy Conservation

CHP complements other energy conservation measures to reduce global energy consumption and thus reduce combustion related emissions. An aggressive energy conservation program can yield savings of up to 30 to 40%. It starts with a thorough review of the process and then moves to optimizing equipment, controls, and utilities. Then and only then should CHP be considered. A CHP system configured to supply the optimum amount of energy can result in, on a global basis, additional energy savings equal or greater than those already achieved through conservation.

The benefits of CHP will only be realized if there is a clear understanding and measurement of those benefits for comparison to other energy options. Unfortunately there is sometimes confusing information about the benefits of CHP. There is no universal standard for reporting the efficiency of CHP systems, which can result in both overstatement and understatement of the benefits of CHP compared to other

power generation systems. Efficiency is an important metric for use in assessing public policy and as a screening tool for economic analysis.

## Fuel Charged to Power

The common metric for measuring the efficiency of thermal power plants is the Higher Heating Value (HHV) heat rate expressed as Btu/kwh (kj/kwh), which is the inverse of efficiency. A useful metric for CHP plants for comparison to other generation and for economic analysis is Fuel Charged to Power (FCP), the energy, net of credit for thermal output, required to produce a kilowatt-hour of electricity. For a plant using a gas turbine or engine including a combined cycle, a simple formula is:

$$\text{FCP} = \frac{\text{Fuel} - \frac{\text{Heat}}{\text{Eff}}}{\text{Power}}$$

Where Fuel is the total Btu/hr of fuel input including the prime mover and, if applicable, supplemental firing; Heat is the total thermal energy delivered to a process which is divided by the combustion efficiency of the alternative heat source; and Power is the kw of net power output. The net power output is the power produced by the combustion turbine or engine and a steam turbine (if applicable) minus parasitic load. The power output can be either electricity or mechanical power or both. Supplemental firing of combustion turbine exhaust will decrease FCP because duct burners use oxygen in the turbine exhaust and thus do not increase stack losses. In addition, the stack temperature actually decreases because the higher temperature differential improves heat transfer rate, particularly in a single pressure level HRSG.

The FCP for a back pressure steam turbine is a special case. It is the conversion factor for kw-hr to Btu divided by the boiler combustion efficiency and the generator mechanical efficiency. Since all of the turbine exhaust is process heat, the incremental fuel is that needed to provide the power output.

$$\text{FCP} = 3412 / \text{Blr Eff} / \text{Gen Eff}$$

For example, if the boiler efficiency is 84% and the generator efficiency is 98%, the FCP is 4145 Btu/kwh. Note that the FCP is independent of the steam turbine isentropic efficiency. This does not mean that isentropic efficiency is irrelevant. Maximizing isentropic efficiency directly increases the amount of very efficient power that is produced saving energy and improving project economics. Maximizing inlet steam pressure and temperature and minimizing exhaust pressure also are key in increasing power output.

The output of cooling can be a source of confusion in determining CHP plant efficiency. While it is technically feasible to use Thermally Activated Cooling (TAC), such as absorption chillers, the inherently low Coefficient Of Performance (COP) compared to mechanical systems reduces the overall system efficiency. The energy displaced by the TAC is power instead of fuel, so the system is analogous to a combined cycle power plant where the prime mover output is enhanced by a bottoming cycle. In fact, for refrigeration loads over a few thousand tons, it is more efficient to use a condensing steam turbine driven mechanical chiller than an absorption chiller. The formula for FCP is:

$$\text{FCP} = \text{Fuel} / (\text{Power} + \text{Cooling} / \text{COP})$$

For the units to be consistent, the cooling output has to be expressed in kw; the COP is for the alternative electric power driven chiller.

## Natural Gas Generation

Natural gas fueled generation provides about 23% of the electric power in the US, but is often the incremental resource. In fact, in some regions natural gas is the marginal fuel for most of the hours of the year. The following table lists the heat rate (Btu/kwh) for natural gas generation alternatives and the typical FCP for CHP plants.

Steam Plants & Peakers	9,500-15,000
GE LMS 100 Simple Cycle	8,500
Combined Cycle (F-Class)	6,900
Combined Cycle (H-Class)	6,300
Gas Turbine CHP (FCP)	3,500-5,000
Gas Engine Jacket Water CHP (FCP)	3,900
Gas Engine/Turbine TAC (FCP)	9,600-14,500

Legacy steam plants and simple cycle gas turbines provide power at the time of peak demand. General Electric now markets the LMS100 gas turbine with a simple cycle heat rate of 8,500. There is a large fleet nationwide of F-class combined cycle plants, and the new H-class plants are even more efficient. CHP plants are able to use the improved gas turbine technology as well. The lowest FCP numbers represent the operation with significant supplemental firing, but a system with an efficient gas turbine and a well designed heat recovery system can operate with a FCP of 4,200 to 4,500 without supplemental firing. Smaller operations that can use heat at a temperature below 200 F can effectively use gas engines with jacket water heat recovery in addition to higher temperature exhaust heat recovery. The FCP of a gas turbine or engine system providing cooling alone is competitive only with peak power.

In some cases CHP systems with TAC appear economic because it is blended with the delivery of thermal energy, because electric rates do not reflect the true marginal cost of generation, or because special incentives are provided based on thermal input to the TAC system instead of power actually avoided. The energy savings and environmental benefits are less than for other natural gas generation options. There

are, however, applications where TAC makes sense. It has been demonstrated that hospitals can use CHP that include TAC to remain in operation after a catastrophe like a hurricane destroys the electric grid. Since hospitals have a demand for thermal energy, a system with the flexibility to operate the TAC system only at peak times when the grid is available would be optimal. Another good application is a data center that requires reliable power and cooling.

The California Public Utilities Commission administers the Self Generation Incentive Program (SGIP) which provides generous subsidies for CHP and other measures that can be installed at customer sites. Performance problems within the program have been documented (1). There are multiple reasons, but certainly the lack of a realistic performance standard is a contributor. The efficiency standard for SGIP is the same as the one promulgated by the US Government for Qualifying (Cogeneration) Facilities (QF) under PURPA around 1980. The goal was to assure that a QF was at least as efficient as a combined cycle power plant, which then had a heat rate of about 8,000 Btu/kwh (compared to 6300 Btu/kwh with current technology). In addition, thermal input into a TAC system is counted instead of the equivalent power reduction. It is possible for a system that has a FCP of around 12,000 Btu/kwh to qualify for incentives.

## Economics

Heat rate and FCP can be used to compare the economics of CHP with other power plants. As demonstrated in the following table, CHP is a very cost effective means of producing dispatchable base load power. The higher efficiency translates into costs for large scale CHP systems that are 30% lower than a natural gas combined cycle unit, which in itself is very competitive with other types of generation. Smaller CHP plants cost more because of the smaller scale and higher gas prices because they are typically connected to a local gas distribution company.

Fixed Charge Rate	15%
Line Loss	7%

	CC Gas	Large CHP	Small CHP
Unit Cost,\$/kw	750	750	1700
Heat Rate, Btu/kwh	6750	4200	4200
Fuel,\$/MMBtu	6.00	6.00	6.50
O&M,\$/kwh	0.011	0.009	0.013
Capacity Factor,%	95%	95%	95%

TYPICAL POWER PRODUCTION COSTS,\$/MWH			
Capital	14	14	31
Fuel	41	25	27
O&M	11	9	13
Generating Cost	65	48	71
Line Loss	5	0	0
Total	70	48	71

The costs are intended to be representative for comparison only. Recent volatility in fuel and construction costs will have a large impact on project economics.

## Biomass CHP

Biomass generation is generally less efficient than fossil fuel generation due to size and combustion characteristics, which means that there is more benefit from CHP because there is more waste heat available for recovery. The following example illustrates the value of CHP in reducing natural gas and water consumption as well as greatly improving project economics. The following table lists the basis for a biomass to energy plant using a steam cycle, the common technology for a plant of this scale. Natural gas is assumed to be the competing fuel for both power and heat.

•Biomass Fuel Consumption	100,000 tpy (dry)
•Capacity Factor	85%
•Biomass Heating Value (LHV)	7,866 Btu/lb
•Steam Conditions	850 psig, 800°F
•Steam Generation	116,000 pph
•Boiler Efficiency	73%
•Natural Gas	
–Cost	\$8/MMBtu
–Combined cycle heat rate	7,000 Btu/kwh (49%)
–Boiler efficiency	83%
•Renewable Energy Credit (REC)	\$10/MWH
•Power Credit	\$81/MWH

If all of the steam is used in a condensing steam turbine, a net of over 10 MW of power is produced and over 100 million gallons per year of water is evaporated for cooling. If the steam is exhausted instead at 150 psig for process, the power output is reduced by about 60%, but 2.5 times as much natural gas is saved with no water use. The improvement in the project economics is dramatic as demonstrated in the following table. The capital investment and Operating and Maintenance expenses are assumed to be equal even though the CHP plant should actually be somewhat less expensive to build and operate since it does not have a cooling system. The project is assumed to qualify for a 30% renewable energy tax credit and the Biomass Crop Assistance Program.

	POWER ONLY	CHP
Net Power, KW	10,370	4,358
Exh Pressure, psia	1.0	165
Heat Rate/FCP, Btu/kwh	16,684	4,817
Water Use, mmgpy	107	-
Nat Gas Saved, mmcf/Yr	520	1283
Nat Gas Saved, \$mm/Yr	4.3	10.7
Rec Value, \$mm/Yr	0.9	0.3
Power Revenue, \$mm/Yr	6.3	2.6
Thermal Revenue, \$mm/Yr	0.0	8.9
EBITDA	0.7	5.5
Payout, Years	12.2	1.6

## **Conclusions and Recommendations**

- CHP systems are most cost effective if designed to supply the optimum thermal energy use and at the lowest temperature.
- CHP systems should be designed to maximize heat recovery and efficient power output.
- Design for flexibility & reliability.
- Use the maximum unit size that will match the thermal requirements.
- Utilize any available by product or waste fuel.
- CHP enhances the economics of biomass to energy.

(1) Performance Assessment Of Cogeneration Systems In California; Kumar Chittory, George Simons, Brad Souza; Itron, Inc.; POWER2007-22114, Proceedings of ASME Power 2007