Cogeneration

Efficiencies and Economics

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ABSTRACT

The magnitude of cogeneration plant efficiency cannot, by itself, prove the plant's feasibility. The most reliable way to determine the feasibility of a cogeneration plant is to compare its performance versus a conventional scheme of generating electric power by a utility and obtaining thermal energy (steam, hot water) from a boiler. For such a purpose, and for comparison of different types of prime movers (steam turbines, gas turbines, combined cycles, and reciprocating engines), the most convenient way is to convert the electric power output into thermal units, and to base the comparison on HHV.

BACKGROUND

Presidents George W. Bush's 2001 new national Energy Policy plan repealed PURPA (Public Utilities Regulatory Policy Act) that was enacted in 1978. The objectives of PURPA 210 were to promote cogeneration that resulted in fuel saving. PURPA legislation established design and operating criteria for the cogeneration plants and mandated utilities to purchase power from the cogenerators at so called "avoided cost."

In general, PURPA 210 led to development of many new cogeneration plants. Unfortunately, some of them were incorrectly sized or had the wrong equipment selection, which reduced their efficiency. In addition, a loophole in PURPA allowed creation of some "PURPA machines" that looked efficient only in the papers submitted to FERC for approval.

I do not see PURPA 210 as a mistake by the legislators (unlike handling of the electric deregulation, especially in California). The fact that some unscrupulous entrepreneurs or developers made mistakes in selecting the cogeneration technology, oversized the equipment, or found some loopholes in this piece of legislation, does not diminish the importance of PURPA in the past. It contributed to technology advances and later spurred the deregulation of natural gas.

TODAY

Currently, while electric utilities deregulation is progressing, the large end users that want stability have many choices: they can continue purchasing power at high cost, they can lease power generating equipment, or they can build their own cogeneration plant if it is feasible.

To make the right economic choice the energy manager should be equipped with the right tools that allow comparing options. One of the selection criteria used by developers is the power plant's overall efficiency. While completely applicable to utility plants or merchant plants generating electricity only, the magnitude of efficiency of a cogeneration plant can be misleading, and not necessarily proves the feasibility of such plant.

In a recent article "How Efficient is 'Efficiency'?" (*Power*, March/April 2001) Dr. Robert V. Peltier raised a good question: how high can cogeneration efficiency be? He ended his article with a subheading entitled "Confused?"

The author did not mention one more item that adds to the confusion: In what terms was the efficiency calculated—Higher Heating Value (HHV) or Lower Heating Value (LHV)? Efficiency based on LHV will have a higher magnitude than the one based on HHV. In the old days of steam turbines and boilers ASME recommended using the HHV.

Nowadays, in the era of gas turbines, it is common to show the efficiency of gas turbines (and reciprocating engines) in LHV. In many cases the manufacturers of gas turbines or engines fail to state that their numbers were based on LHV.

As the readers know, combustion of fuels having hydrogen produces water vapor. If the products of combustion are at high temperature, the water will leave the system as a vapor and will carry with it energy equivalent to the energy of superheated steam.

LHV assumes that the water vapor has not been condensed and, therefore, carries the additional energy. The specific value of LHV of a given fuel depends on the fuel composition. For a typical natural gas composition the LHV equals approximately 90% of HHV. Therefore, some manufacturers that show both the LHV and HHV use 0.9 as the ratio between LHV and HHV. When comparing different plant technologies, it is important to bring all of them to a common 'denominator'. Usually it will be HHV.

In addition, as I mentioned before, the magnitude of cogeneration plant efficiency could not by itself prove the plant's feasibility. The most reliable way to determine the feasibility of a cogeneration plant is to compare its performance versus a conventional scheme of generating electric power by a utility and obtaining thermal energy (steam, hot water) from a boiler. For such purpose and for comparison of different types of prime movers (steam turbines, gas turbines, combined cycles, and reciprocating engines) the most convenient way is to convert the electric power output into thermal units, and to base the comparison on HHV.

THERMAL-TO-ELECTRIC LOADS RATIO

In my article "Cogeneration: Where Will it Fit in the Deregulated Market?" (*Cogeneration and Competitive Power Journal*, spring 1998) I emphasized the importance of the thermal-to-electric loads ratio (HPR) for selecting the right type of prime movers that would most closely match the thermal and electric load demand and profile.

However, even the best matching technology would not guarantee the feasibility of a cogeneration plant unless the prime movers are correctly sized. Oversizing of a turbine or engine reduces the annual hours of utilization of the prime mover capacity, unless it is specifically intended to cover peak loads.

Equally, the annual load profile or the annual hours of utilization of thermal loads of the user are critical in determining the feasibility of a cogeneration plant. If such numbers are below 4000 hours per year the savings will be low, and the cogeneration plant may not be feasible at all. If the numbers are above 6000 hours/year (ideally the range would be 8000 to 8500 hours/year) the cogeneration plant would deliver substantial savings. The notorious 'PURPA machines' were the result of selecting incorrect types of equipment, equipment oversizing, or overestimating the annual loads.

Table 1 below provides a comparison of various technologies selected to match certain HPR, **having one common base—the same size thermal load**. The table shows cogeneration plant total efficiency corresponding to various HPR. In addition, it compares cogeneration efficiency versus the total (combined) efficiency of a conventional scheme, i.e. of a utility unit generating a respective amount of electric power, and a boiler providing the same thermal output as the cogeneration plant.

The thermal load assumed for all the cases was 25,000 lb/hr 130-psig saturated steam output. The cogeneration plant prime movers in Table 1 were a Solar Centaur 50 gas turbine, a 'generic' lean-burn reciprocating engine (no specific manufacturer, a typical electrical efficiency assumed), and two backpressure steam turbines with different inlet pressures (600 psig and 1500 psig). Since the backpressure turbines with the above inlet pressures and corresponding inlet temperatures 750°F and 900°F respectively would discharge superheated steam at 130 psig, desuperheating by injecting 227°F feedwater was assumed, and the steam inlet flow reduced accordingly to generate 25,000 lb/hr saturated steam output.

COMPARISON

For comparison, two types of utility turbine generators were considered: a 500 MW combined cycle based on a 107H technology, and a 500 MW condensing steam turbine with subcritical inlet parameters. Natural gas was assumed as the prime fuel in all cases. The boiler efficiency was assumed 85% corresponding to a modem boiler with an economizer.

The utility unit's performance was based on the net heat rate (HR)-HHV as shown in *Power Engineering* magazine, November 1997 (6,793 Btu/kW-hr corresponding to 50.2% HHV efficiency and 55.8% LHV efficiency for the combined cycle, and 9,612 Btu/kW-hr corresponding to 35.5% HHV efficiency for the condensing unit).

There is no need to mention that the HR and efficiency are related, and the higher the efficiency the lower will be the HR. (I recall, when I first started my career in the United States in 1977, working for a large engineering firm developing and designing utility power plants, I was

Table 1. Comparison of various cogeneration technologies versus conventional schemes of power generation.

Type of Prime Mover For Cogeneration Plant	Cogen. Gross Electric Output kW	Heat-to-Power Ratio (HPR)	Cogen. Electrical Efficiency (HHV) %	Cogeneration Total Efficiency %	Conventional Scheme (with Combined Cycle) Total Efficiency %	Conventional Scheme (with Condensing Turbine) Total Efficiency %
Reciprocating Engine(s)	16,000	0.46	38.0%	45.9%	55.2%	44.4%
Gas Turbine (Centaur 50) ISO conditions	4,345	1.68	26.3%	71.0%	66.0%	57.0%
Backpress. Steam Turbine 1500 psig/900°F inlet *	1,100	6.64	68.6%	79.0%	77.0%	72.3%
Backpress. Steam Turbine 600 psig/750°F inlet *	600	12.2	62.7%	82.0%	80.0%	77.1%

*Note: Coal-fired boilers equipped with an air heater, while burning high quality low-moisture coal, may provide efficiencies higher than 85%, e.g. 90% to 92%. Therefore, the total efficiency of a coal-fired cogeneration plant with steam turbines may be higher than the one shown in the above table.

surprised that company guidelines for calculating the heat rate did not give credits to units with extraction steam turbines supplying steam for over-the-fence process needs). The higher was the extraction steam flow, the higher was the corresponding HR, implying turbine performance deterioration.

The right way would be to subtract the value of thermal energy delivered by the extraction turbine, thus allocating a lesser amount of fuel for power generation, and lowering the HR.

In a cogeneration plant various methods may be used for allocating portions of the auxiliary ('parasitic') power between the electric power generation and thermal energy for the purpose of estimating the cost of that power and heat. Similarly, such allocation should be performed for proportioning the annual O&M expenses. In real life, commercial 'cogenerators' may artificially reduce the price of thermal energy to make up by a higher electricity price.

For the sake of simplification, in Table 1 the comparison was based on a gross output, not net output. To convert the net HR of the utility units to gross HR, a 2.5% parasitic power for a combined cycle and 6% for a condensing turbine unit was assumed. In addition, for the utility units the electric power had to be delivered to the point of user interconnection, therefore, for the comparison, the utility HR was penalized with 5% transmission loss.

The total efficiency of a cogeneration plant or of a conventional scheme is the ratio of the total energy output (electric and thermal) to the energy of fuel input (HHV). For conversion of the electric output (gross) to thermal units a simple formula was used:

$Q_{el} = N_{el} \times 3413/\eta_{gen}$, where

Q_{el} - useful electric energy (gross) in Btu/hr;

N_{el} - generator(s) electric output, kW;

η_{gen} - generator(s) efficiency;

3413 Btu/kW - rounded conversion factor.

The generator efficiency η_{gen} was assumed as follows: 98% for the cogeneration plant generators, and 99% for the utility generators.

The assumed total electric turbine/generators and engine/generators efficiency at 100% load (HHV) is shown in the referenced table.

As can be seen from Table 1, backpressure steam turbines would have the highest cogeneration total efficiency range, the reciprocating engines provide the relatively lower end, and the gas turbines are in between. The same hierarchy shall be observed for matching the applicable technology to the HPR, i.e. steam turbines should be used for HPR exceeding 2.5-3.0, gas turbines for HPR in the range of 1.0 to 2.5, and reciprocating engines are the best application for HPR lesser than 1.0.

A combined cycle with a steam turbine operating in a condensing mode will be applicable for HPR in the same range as the reciprocating engines. The HPR range recommendations here are approximate. Design of a cogeneration plant is always site specific, therefore it is important that load data and the selected equipment performance are scrutinized before it is installed.

For example, a reciprocating engine providing hot water of 180°F would match an HPR approaching 1.0. Reciprocating engine(s) with the same 38% electrical efficiency as the one shown in Table 1, but supplying 195°F hot water would have an HPR 0.9 and total gross efficiency 73.5% (HHV), much higher than the 45.9% of the one supplying 130-psig steam.

Gas turbines of special design such as those licensed under the Cheng Cycle may also have an HPR below 1.0 when operating with full steam injection. Cheng cycle gas turbines are designed to handle high volumes of steam injection to augment their electric output.

Steam generated from a heat recovery steam generator (HRSG) may in part be diverted from the thermal energy user to the gas turbine for injection. This would reduce the HPR. On the other hand, HRSG with supplemental firing can increase their thermal output, rising the HPR. Respectively, the overall plant efficiency may go up to 82% (HHV) and higher. Similarly, when a combined cycle with an extraction turbine operates at full extraction and minimum condenser flow the HPR increases. Thus, in certain cases the HPR can be variable.

In addition, Table 1 demonstrates that a conventional scheme of generating electric power even by a most efficient utility unit, and supplying thermal energy from a boiler, is in most cases less efficient than generating the same amount of energy by a properly designed cogeneration plant. Cogeneration saves fuel and, as a result, generates less pollution.

CONCLUSIONS

1. Not all cogeneration technologies are equally applicable in all cases. A "one size fits all" philosophy does not work.
2. Each technology has its own range of electrical and total cogeneration efficiency depending on the heat-to-power ratio.
3. Selection of the optimal technology and size shall be determined by the type of the thermal load (high-, medium- or low-pressure steam, hot water), heat-to-power ratio and annual load profiles.
4. Cogeneration saves fuel and reduces pollution.
5. A properly designed cogeneration plant is more efficient than a conventional scheme of generating electricity and heat, even when compared against modern highly efficient utility units.
6. Not only industrial cogeneration but also institutional and some commercial cogeneration is feasible when a proper combination and size of heating and cooling loads is in existence.

ABOUT THE AUTHOR

Dr. Moisey Fridman is a consultant for engineering companies on the West Coast. He is an expert in cogeneration and power plants, industrial energy supply, and District Heating and Central Cooling systems. Currently he serves as an advisor and consultant on numerous cogeneration feasibility studies for California state universities. Previously he was with LG&E Power as a lead engineer and consultant, and with Sargent & Lundy's (Chicago, IL) analytical division as a senior engineering specialist on cogeneration and combined cycle power plants.

Dr. Fridman was involved in the development, engineering and design of numerous cogeneration power plants in the United States, Europe and Asia, serving as a group leader, project manager and advisor to special task groups. He has worked in the U.S. since 1977. He received his MS degree in mechanical engineering from Kiev Polytechnic Institute (USSR) and a Ph.D. degree in cogeneration from Moscow Energy Institute. Having worked for major engineering and research companies, he has over 30 years experience in energy source development around the world. He is also a registered professional engineer in the states of Illinois and California.

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