
Efficiency Improvements with Small Cogeneration

Sven Erlandsson

Director, Application Engineering

Steam Turbines and Industrial Gas Turbines

ABB Power Generation Inc.

Cogeneration efficiency is sometimes misunderstood. Different views are taken, depending on who is evaluating a project. The question should be asked if the main purpose is to generate electricity while producing heat as a by-product—or—should a given heat energy demand be considered as an opportunity for highly efficient generation of electric power?

This article will take the latter approach (By-Product Power Generation) and will define some of the relations between heat energy, electric energy and “lost” energy. Different ways of maximizing and optimizing the cogeneration benefits will be demonstrated. Examples will cover steam turbine, gas turbine and combined cycle plants.

HEAT ENERGY GENERATION AND USE IN INDUSTRIAL AND HEATING PLANTS

There are several different types of heating sources and uses in the industry (and for District Heating Systems):

- Steam used for an industrial process or for space heating.
- Hot water used for an industrial process or for space heating.
- Direct firing of an industrial process (such as a kiln).

- An exothermic industrial process (providing heat energy).
- Fuels provided by an industrial process (such as Black Liquor in the wood pulp industry or Low BTU gas in the steel industry).
- Waste material, which can be used as fuel (such as garbage, bark and wood waste).

Each one of these situations provide an opportunity for By-Product Power generation (BPP-generation). The common factor is that the heat energy situation is fixed. The possibility for BPP-generation can therefore be evaluated as an incremental investment, providing an incremental benefit.

BALANCE BETWEEN BPP-GENERATION AND POWER DEMAND

Some industries use a lot of electric energy. BPP-generation can be used to decrease the amount of purchased power. This seems to be a clear-cut solution, but there is sometimes a problem to balance the BPP-generation with the Power Demand in the industrial plant.

Short time and seasonal variations in both BPP-generation and Power demand do very seldom follow each other. That means that the following can occur:

- Large swings in the requirement for purchased power.
- Swings between excess BPP at one instance to requirement for purchased power at another instance.
- Excess By-Product Power (BPP), but varying (sometimes heavily) with time.

In the past, it has been difficult to negotiate an attractive power contract that allows for these swings. Swings in purchased power have been penalized by heavy Demand Charges - or - when selling power, the power utilities wanted either a constant flow of electric power or power only when requested (dispatched).

Therefore, most existing BPP-generation plants do have internal facilities to “balance” the power generation:

- “Condensing Tails” on steam turbines.
- “Duct Firing” on combined cycle plants.
- “Steam Dumping.”

Some new approaches include:

- The sale of all BPP-generation to a power company on one contract and purchase of all power for use in the industrial plant on another, separate contract.
- Power Wheeling (buying required power balance or selling excess BPP-generation on the “spot market”).

It is important to explore all avenues, because the need for “balancing” can decrease the benefit of the BPP-generation.

The effectiveness of BPP-generation can also be expressed as a BPP-rate (By-Product-Power rate) related to the (fixed) process heat demand.

The BPP-rate is a more useful tool than the heat rate when it comes to evaluate different turbine generator and plant data. This will be demonstrated by the examples that follow.

Both turbine-generators have the same thermo-dynamical, mechanical and electrical efficiency, and therefore the heat rate is the same. However, with the higher steam inlet data, 3,270 kW of extra power is generated for the same process heat demand (the BPP-rate is higher).

It is assumed that the process needs to receive the steam at a temperature of 338 F (about 10 F superheat). In the previous examples, the turbine inlet temperature has been selected to provide the correct turbine exhaust temperature (assuming a turbine blading with 88% thermodynamic efficiency).

Operating a turbine with 85% efficiency instead of 88% would decrease the power output by 3.4% if the steam flow through the

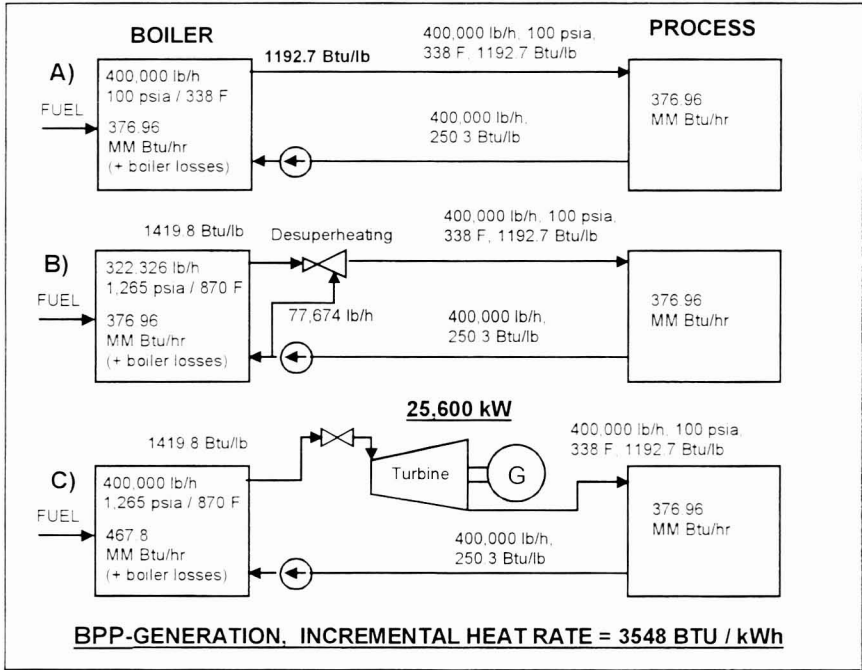


Figure 1. The Back Pressure Steam Turbine Cycle

Adding a back-pressure turbine between the boiler and an industrial process.

- A) Without BPP-generation, the heat demand requirements of an industrial process can be satisfied by steam from a LP boiler.
- B) The steam can also be supplied from a HP Boiler, via a pressure reducer/ desuperheating station. The amount of energy supplied by the feed water pump and boiler will be approximately the same as for the LP boiler alternative.
- C) Instead of going through the pressure reducer and desuperheating, the steam can pass through a back pressure turbine. In this example, the turbine has a thermodynamic efficiency of about 88% and will generate 25.6 MW of electric power. The power is not free, as the boiler will have to produce an additional 90.4 MMBtu of heat output but the “Incremental Heat Rate” for the electric power generation is only 3548 Btu/kWh.

turbine remained the same. However, a less efficient turbine exhausts the steam with a higher enthalpy. Spray water is therefore required to cool down the steam flow to the process. In Figure 3B, 0.8% of the steam going to the process is coming from the cooling water and therefore the steam flow through the turbine will decrease with 0.8%.

Consequently, the less efficient turbine will generate 4.2% (1,075 kW) less power than the more efficient one. The BPP-rate will decrease

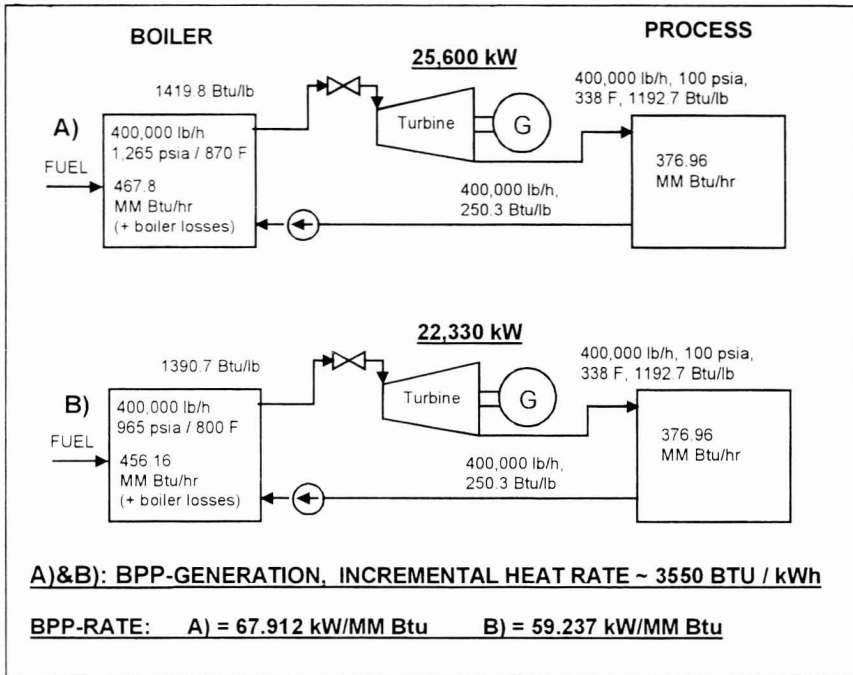


Figure 2.
Different Boiler (Turbine Inlet) Steam Conditions

2A) 1,265 psia/870F.

2B) 965 psia/800F.

In this example, $25,600/376.96 = 67.912$ kW per MMBtu of process heat demand.

from 67.912 to 65.06 kW/MMBtu to the process. The interesting part, however, is that the less efficient turbine will operate with about the same heat rate, because the required heat input from the boiler decreases.

Both turbines perform best with high steam temperature (Figure 3). Using 850 F instead of 870 F decreases the output with about 1.500 kW for turbine 'A' (which requires heating of the exhaust steam with the lower inlet steam temperature) and 500 kW (for turbine 'B', which requires exhaust desuperheating with the higher inlet steam temperature).

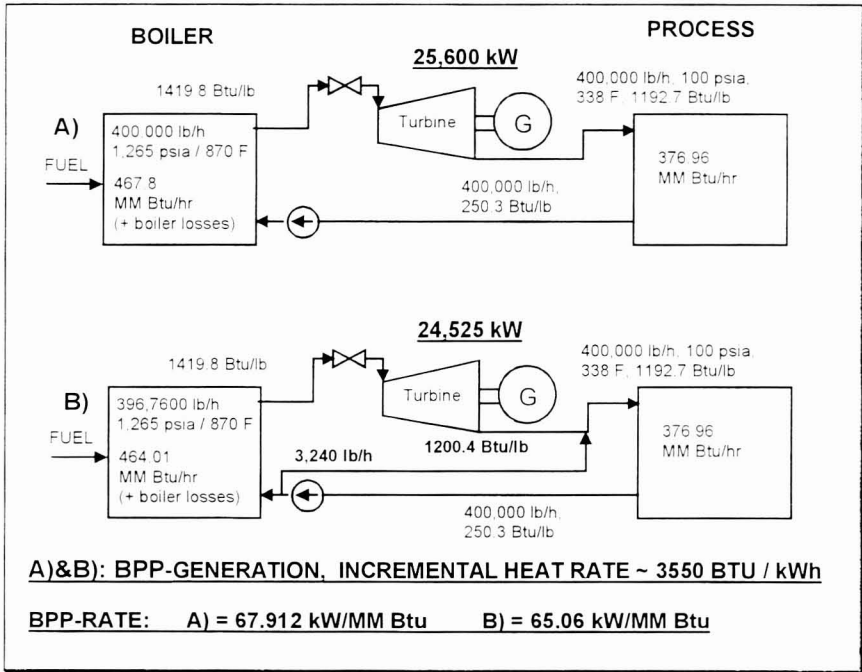


Figure 3. Different Thermodynamical Efficiency

- 3A) Thermodynamic efficiency = 88%.
- 3B) Thermodynamic efficiency = 85%.

In a case where the boiler cannot provide high enough temperature to keep the exhaust of a high-efficiency turbine superheated, it is still better to use a highly efficient turbine (1,000 kW better in Figure 4). The use of an heat exchanger for the exhaust steam provides this 1,000 kW advantage over the turbine with lower efficiency.

Figures 5a and 5b show the results of increasing the Turbine Efficiency, increasing the Inlet Steam Temperature, lowering the Back Pressure and adding Feed Heating.

The heat rate (heat requirement in addition to the heat requirement of the industrial process) is still at about 3,550 Btu/kWh, but the BPP-rate has been increased from 67.9 to 87.28 kW/MMBtu (of the process heat requirement).

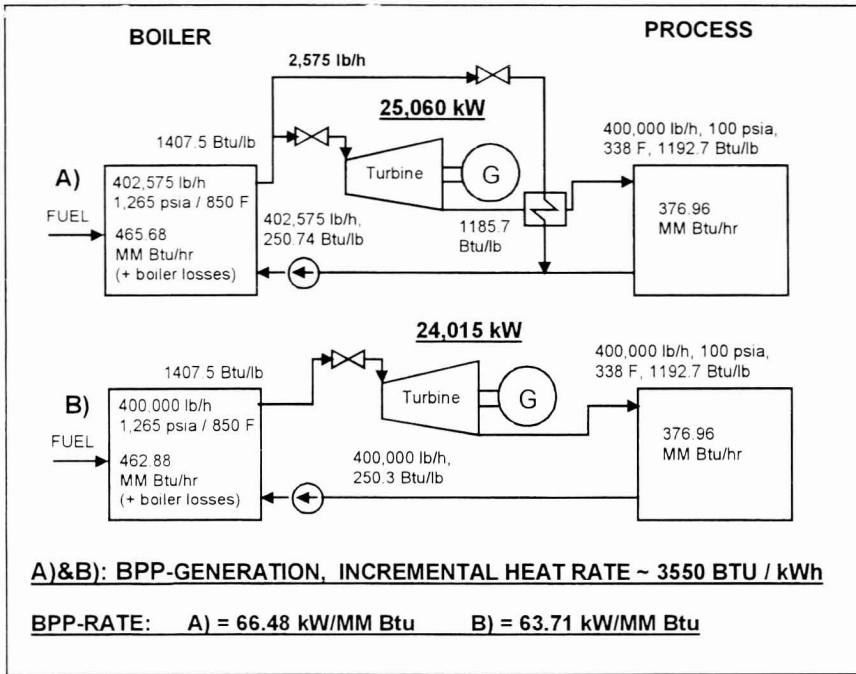


Figure 4. Lowering the steam inlet temperature

Figure 4 uses 850 F steam inlet temperature but is otherwise the same as figure 3 (which used 870 F).

4A) Thermodynamic efficiency = 88%.

4B) Thermodynamic efficiency = 85%.

The electric power generation has increased with 7.300 kW (from 25,600 to 32,900 kW). That is a 28.5% improvement.

The HP feed heater addition improves the power output with 2.360 kW, because the steam flow through the front end of the turbine increases with 78,000 lb./h (with the same back end heat flow to the process).

The lowering of the back pressure from 100 psia to 75 psia provides 2.300 kW. That indicates the need to take a look at the process itself (can it operate with a lower steam pressure) as well as the pressure drops between the turbine exhaust and the process.

The effects from the inlet steam pressure inlet steam temperature and thermodynamic turbine efficiency have already been covered.

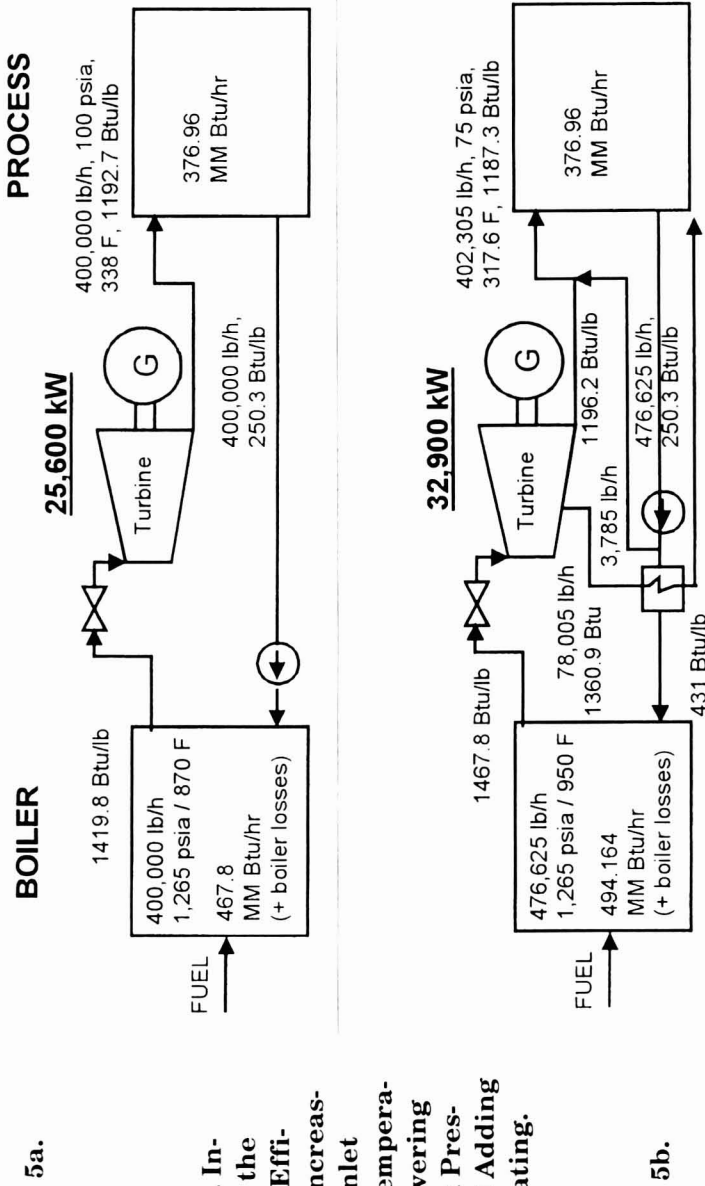


Figure 5. Increasing the Turbine Efficiency, Increasing the Inlet Steam Temperature, Lowering the Back Pressure and Adding Feed Heating.

- 5A) The "basic" turbine generator with 88% thermodynamic efficiency
- 5B) An optimized plant, with 90% thermodynamic efficiency, increased steam inlet temperature, lowered back pressure (assuming that the process allows - still supplied with the same Heat Flow). A HP feed heater has been added (it has been assumed that LP heating/Deaerator is part of the industrial process).

There is no “lost energy” when operating back pressure steam turbine-generators, except for some small mechanical and electrical losses.

With a fuel price of \$4.00/MMBtu, this type of power generation will operate with a fuel cost of 1.42 cents/kWh (and proportionally lower with less costly fuel). The investment cost and the maintenance cost is very low for back pressure steam turbines (especially when considering that the boiler as such is required in any case, to cover the process heat demand).

Industrial processes very often use steam at two different pressures. The HP steam is taken out through an extraction point, while the LP steam continues to the back end of the turbine (generating electric power).

Everything that has been said about Back Pressure Turbines is also valid for Extraction - Back Pressure Turbines:

The heat rate is always approximately 3,550 Btu/kWh (extra heat supplied by the boiler over and above what is required for the process need). However, the effectiveness of the turbine generator need to be evaluated using the BPP-rate (By-Product Power Rate).

It is of course also possible to use two individual turbine generators (in parallel), with each one exhausting to its own process steam pressure. This can increase the BPP-rate considerably in some cases, depending on how the process steam flow may vary.

Operating a steam turbine with varying steam flow:

The optimized plant in Figure 5B assumed 90% thermodynamic turbine blading efficiency. This is normally only achievable when the

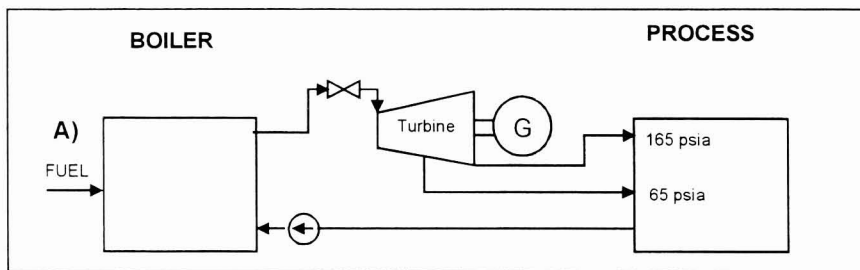


Figure 6. Extraction—Back Pressure Steam Turbines

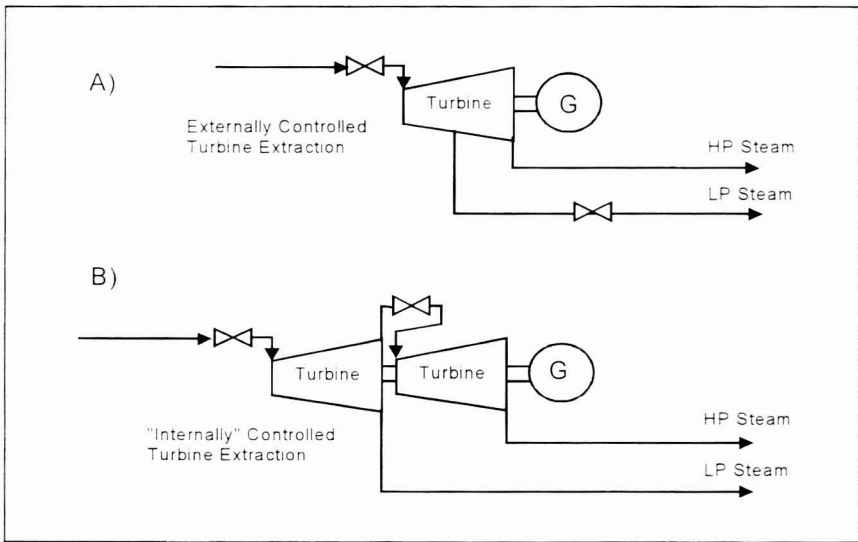


Figure 7. Different Extraction Arrangements

- 7A) The extraction is controlled by an external valve, and the pressure at the extraction point is "sliding." This means that the pressure is depending on how much steam is "forced" through to the back end of the turbine. This type of extraction is very suitable when the extraction steam flow is small, when compared with the steam flow to the exhaust.
- 7B) This type of turbine functions as two turbines in series with each other, with control valves at the inlet of each turbine. There can be two individual turbine casings, but these are normally built within the same casing and with the control valves located inside the casing (therefore the "internal control"). With this type of extraction, the flow to the back end of the turbine can be decreased so that almost all steam goes out through the extraction. This type of extraction is suitable for large (and widely varying) extraction flows.

turbine is operating close to its "best" operating point. Extraction Back Pressure turbines seldom reaches that efficiency, because in most cases either the HP or the LP part will not operate at its "best point." The control valves (external or external) will, if operating in throttling position, introduce losses.

To keep the thermodynamic efficiency (and thereby the BPP-rate) high, the turbine and control valve arrangement should be carefully evaluated. There are several ways available:

- The flow capability of a turbine section (inlet valves wide open) should be designed for the normally expected steam. If the turbine is too large, valves will have to throttle the steam flow (lowering the efficiency).
- For higher steam flows than normal, it is possible to equip a turbine with an “overload-bypass” valve that puts in additional steam at a location further down in the turbine (not passing through the first couple of turbine stages). If these peaks are short-term, it pays to use a bypass valve and have the turbine inlet section dimensioned for “normal flows” (not for the max flows).
- It is possible to add an external control valve (in the extraction steam pipe) also to an “internally controlled” extraction turbine. If the LP section of the turbine is designed for the “normal” LP steam flow to the process, an external valve can, if closed, increase the pressure at the extraction port and thereby “force” additional steam to pass to the back end of the turbine. The internal valves will be active when “less than normal” LP steam is required.
- Finally, if the boiler and the turbine are dedicated to each other and the boiler can operate with varying pressure, consider “sliding pressure” operation (with wide open turbine inlet valves).

Maximize the BPP-rate of the extraction/back pressure power generation first (with a heat rate of about 3550 Btu/kWh). Then make the condensing part as efficient as possible and evaluate the condensing power separately, as an increment.

Although it most certainly will pay to purchase fuel for BPP-generation, condensing power generation with purchased fuel can be questionable.

If using an incremental approach:

1. The requirements for process heat must first be covered.
2. The BPP-generation should be maximized. As much power as possible should be generated at the low heat rate of 3,550 Btu/kWh.

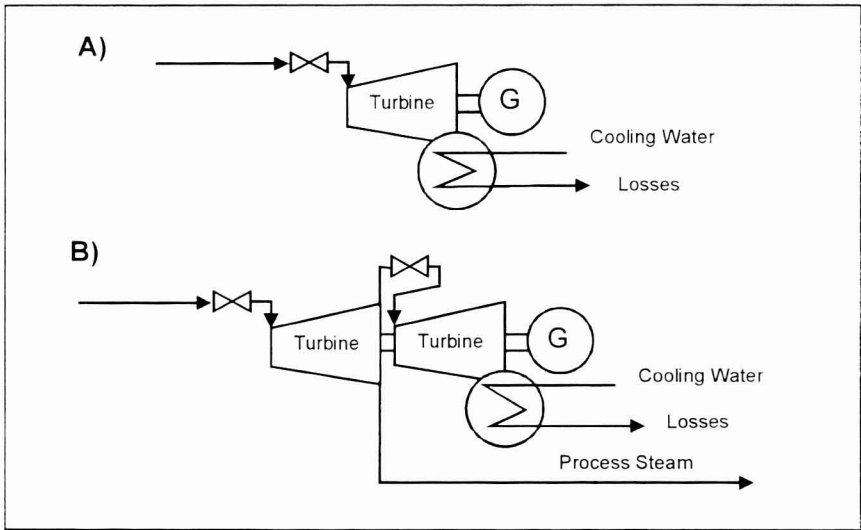


Figure 8.

Condensing or Extraction/Condensing Steam Turbines

As soon as a condensing steam turbine is installed, there is a large loss to consider, namely the heat energy that is removed by the condenser.

There are two reasons for installing industrial condensing steam turbines:

- 8A) The availability of excess fuel or heat, which cannot be used otherwise. This is well worth pursuing. Steam at atmospheric pressure can generate quite an amount of electric power in a condensing steam turbine generator. With higher steam data, even more can be generated. The evaluation here is based on the fixed amount of excess heat available (rather than on the fixed heat demand by an industrial process). The benefit is not related to cost of fuel, but to the cost of electric power (and the amount of power that can be generated).
- 8B) The need for "balancing" between BPP-generation and Power Demand. This should be carefully evaluated. Consider the alternative of a contract with an electric power company, allowing the load swings to be handled by a much larger power system. Condensing turbines using steam generated by purchased fuel have to be evaluated on the basis of heat rate (which can vary widely, depending on inlet steam pressure and temperature, condenser pressure, turbine efficiency and feed water heating arrangements). Note that the condensing cycle (due to the condenser losses) will have a heat rate that is more than twice as high as (extraction) - back pressure power.

PROCESS GENERATED HEAT	WASTE FUEL	PURCHASED FUEL
PROCESS HEAT DEMAND	BPP-GENERATION (EXTRACTION) BACK PRESSURE	CONDENSING POWER GENERATION

Figure 9. Use of Different Fuels

3. When coming to the condensing power generation (at a much higher heat rate), it is important to look at the cost of the incremental fuel requirement.

The use of gas turbines becomes attractive, when higher electric power output is required. The 47,500 kW indicated in Figure 10 is more than can be achieved with an optimized back pressure steam turbine cycle (compare with figure 5B).

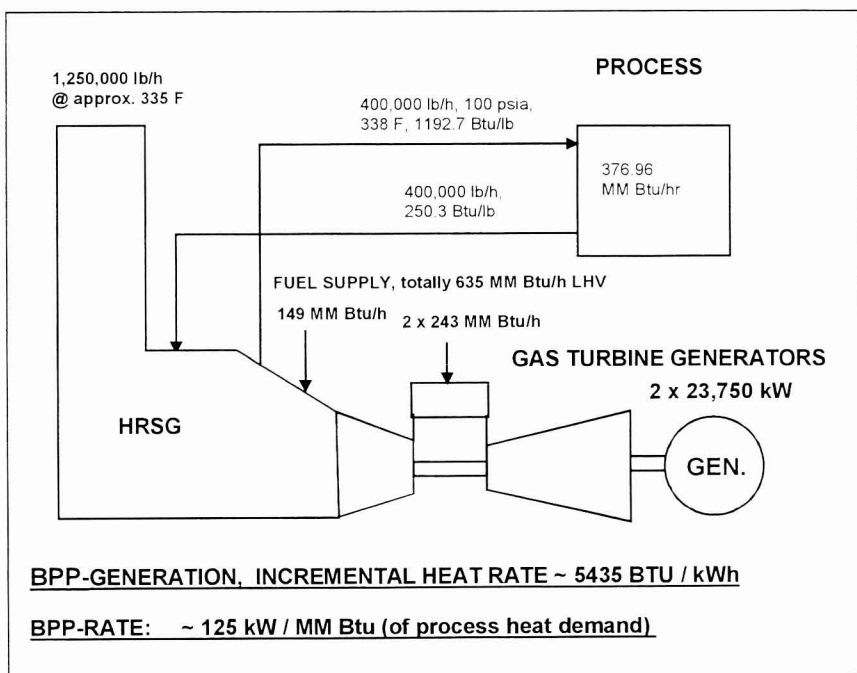


Figure 10. The Gas Turbine Cycle

There are stack losses due to a flow of warm gases. The heat rate for power generation (fuel used in addition to the process heat demand) indicates a cycle efficiency (for power generation) of about 63% (which is higher than what is possible in a single purpose electric power plant).

The incremental gain above figure 5B is about 14,600 kW, for an additional fuel input of 140 MMBtu/h. This means that the heat rate for the increment is about 9590 Btu/kWh (35.6% efficiency). This is better than for an industrial condensing steam turbine.

This gas turbine cycle is not optimized. There are many parameters to consider, including elevation, ambient temperature, etc. One item that can lower the stack losses is to return the condensate from the process at a lower temperature (it is not necessary to provide feed heating outside of the HRSG).

Duct firing provides the flexibility for balancing the process heat demand. Note that the heat flow from the duct firing will go to the industrial process as 100 % usable energy (it will normally not increase the stack losses). This is different from single purpose electric power generation, where duct firing to increase the output of a condensing steam turbine causes an increase in the condenser heat losses.

With a third gas turbine added, the plant balance allows for the addition of a back pressure steam turbine, which can utilize the possibility of generating high pressure steam. The exhaust of the steam turbine is mixed with steam from a LP boiler in the HRSG.

This gives an additional electric power generation of 49,500 kW for an additional fuel input of 225 MMBtu (a heat rate of 4545 Btu/kWh or an efficiency of 75% for the increment).

SUMMARY

This article has pinpointed some components of cogeneration efficiency, how these components interact with each other and how they contribute to the end result. There are really only two things to think of:

1. Eliminate or minimize wasted energy flows (cooling water losses and stack losses).

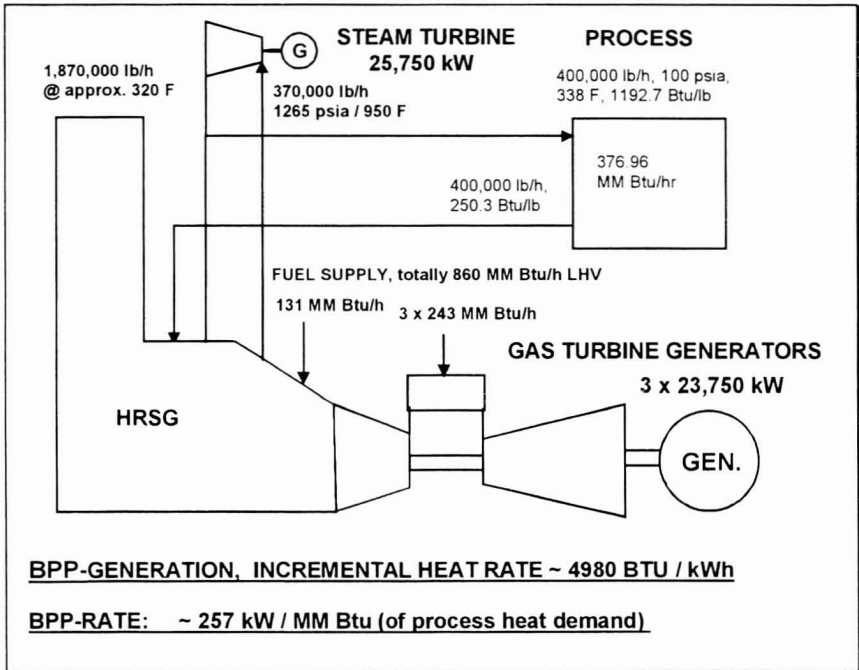


Figure 11. A Combined Gas and Steam Turbine Cycle

2. At the same time, maximize the electric power generation for a given industrial process.

ABOUT THE AUTHOR

Sven Erlandsson is Director of Application Engineering, Steam Turbines and Industrial Gas Turbines Division, ABB Power Generation, Inc., Midlothian, VA. Phone: 804-763-2330.