National Environment Agency Singapore

Measurement & Verification of Heating Systems

We Deliver.

1 Cogeneration System

Cogeneration is defined as a combined heat and power system that simultaneously generate electrical power and heat for process use.

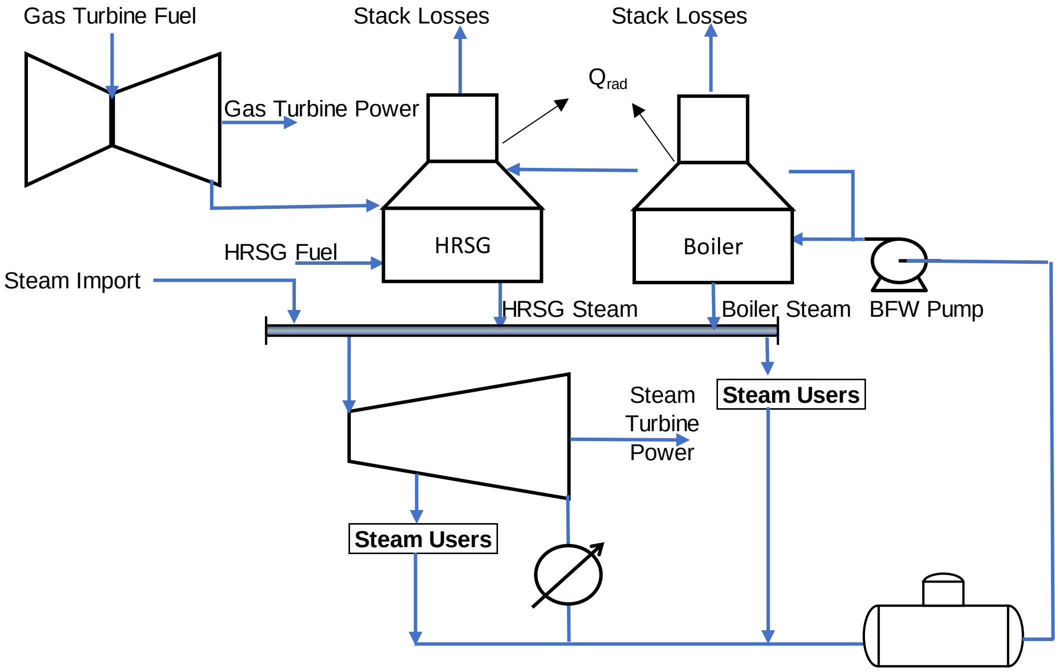


Figure 1: Simplified sketch of a cogeneration system

Table 1: Key energy metrics for cogeneration systems

Energy System	Hierarchy	Metric	Method
Entire cogeneration system	Energy performance indicator	Thermal efficiency (%)	Calculated
	Energy performance indicator	Energy performance gap (%)	Calculated
Gas turbine only	Energy performance indicator	Thermal efficiency (%)	Calculated
HRSG only	Energy performance indicator	Thermal efficiency (%)	Calculated
	Energy influencing variable	HRSG stack temperature (°C)	Measured
Steam turbine only	Energy performance indicator	Thermal efficiency (%)	Calculated
General steam and condensate system	Energy performance indicator	Overall mass / energy balance of steam system	Calculated
	Energy performance indicator	Condensate recovery (%)	Calculated
	Energy performance indicator	BFW pump specific energy consumption (kW/unit throughput)	Calculated
	Energy influencing variable	Deaerator pressure	Measured

Energy performance indicators: these are calculated values that allow the management and engineering team to track the overall performance of an equipment, process or even the whole site.

Energy influencing variables: these items represent elements within the system that can be manipulated to improve the efficiency of the equipment or process.

Figure 1 shows a schematic diagram of a typical cogeneration system. Table 1 shows a list of key metrics for a cogeneration system.

This measurement and verification (M&V) plan serves to outline the methodology for quantifying the energy improvement before and after the implementation of energy conservation measures relating to the cogeneration system.

2 Assessment of Baseline Energy Performance

2.1 Overall thermal efficiency of cogeneration system

The overall thermal efficiency of the cogeneration system can be computed using the following methodology.

$$Site\ Power\ Demand_{baseline} = \left(Power_{GTG,baseline} + Power_{STG,baseline} + Power_{IMP,baseline}\right) \quad \text{Eqn. 1}$$

$$Steam\ Heat\ Demand_{baseline} = (m_{steam} \times H_{steam}) - (m_{cond} \times H_{cond}) \quad \text{Eqn. 2}$$

$$Fired\ Fuel = (m \times LHV)_{GTG\ fuel} + (m \times LHV)_{HRSG\ fuel} + (m \times LHV)_{boiler\ fuel} \quad \text{Eqn. 3}$$

$$Imported\ Steam\ Heat = \frac{m_{import} \times H_{import}}{E_{import}} \quad \text{Eqn. 4}$$

$$Imported\ Power = \frac{Power_{IMP,baseline}}{E_{P,\ import}} \quad \text{Eqn. 5}$$

$$E_{cogen,baseline} = \frac{Site\ Power\ Demand_{baseline} + Steam\ Heat\ Demand_{baseline}}{Fired\ Fuel + Imported\ Steam\ Heat + Imported\ Power} \times 100\% \quad \text{Eqn. 6}$$

Where:

Site Power $Demand_{baseline}$	:	Total baseline electrical power demand (kJ/h)
$Power_{GTG,baseline}$	:	Baseline power output of GTG (kJ/h)
$Power_{STG,baseline}$	:	Baseline power output of STG (kJ/h)
$Power_{IMP,baseline}$	:	Baseline power imported (kJ/h)

Steam Heat Demand$_{baseline}$	:	Total baseline steam heat to users (kJ/h)
m_{steam}	:	Mass flow rate of steam sent to users (kg/h)
H_{steam}	:	Steam enthalpy (kJ/kg)
m_{cond}	:	Mass flow rate of condensate returned from users (kg/h)
H_{cond}	:	Return condensate enthalpy (kJ/kg)
Fired Fuel	:	Rate of total fuel fired (kJ/h)
$M_{GTG\ fuel}$	:	Mass flow rate of fuel sent to GTG (kg/h)
$LHV_{GTG\ fuel}$	:	Lower heating value of fuel sent to GTG (kJ/kg)
$M_{HRSG\ fuel}$	:	Mass flow rate of fuel sent to HRSG (kg/h)
$LHV_{HRSG\ fuel}$	:	Lower heating value of fuel sent to HRSG (kJ/kg)
$M_{boiler\ fuel}$	:	Mass flow rate of fuel sent to boiler (kg/h)
$LHV_{boiler\ fuel}$	:	Lower heating value of fuel sent to boiler (kJ/kg)
Imported Steam Heat	:	Steam heat imported into cogeneration system (kJ/h)
m_{import}	:	Mass flow rate of steam import (kg/h)
H_{import}	:	Enthalpy of steam import (kJ/kg)
E_{import}	:	Efficiency of steam generation for steam import, assume 92% if unknown (%)
Imported Power	:	Electricity imported into cogeneration system (kJ/h)
$E_{p,\ import}$	:	Efficiency of generation for imported power, assume 38% if unknown (%)
$E_{cogen,baseline}$	:	Overall baseline thermal efficiency of the cogeneration system (%)

2.2 BFW pump specific energy consumption

The power consumption of pumps can be determined by one of the following methods

- Use of readings from existing power meters

  Power consumption of pumps can be measured through the use of existing power meters or ammeters. If power meters are available, then power consumption information will be available for applying *Eqn. 7* below.

- Plot baseline operation on the pump curve

  Using the operating flow data of the pump, the pump curve can be used to determine the pump power consumption.

Specific energy consumption (SEC) of a pump can be computed by the following formula.

$$SEC_{baseline} = \frac{Pump\ Power_{baseline}}{Unit\ throughput} \qquad \textit{Eqn. 7}$$

Where:

$SEC_{baseline}$	:	Baseline specific energy consumption of pump (kWh/t)
Pump $Power_{baseline}$	:	Baseline power consumption of pump (kW)
Unit $throughput_{baseline}$	:	Baseline pump fluid flow rate (t/h)

3 Assessment of Post-Implementation Energy Performance

The assessment of post-implementation energy performance of a cogeneration system follows the same approach as detailed in Section 2 above.

4 Quantification of Energy Performance Improvement and Cost Savings

Energy performance improvements to the cogeneration system can be quantified as follow.

$$Energy\ performance\ improvement = Fired\ Fuel\ Improvement + Imported\ Steam\ Improvement + Imported\ Power\ Improvement \qquad Eqn.\ 8$$

$$Fired\ Fuel\ Improvement = Fired\ Fuel_{post} - Fired\ Fuel_{baseline} \qquad Eqn.\ 9$$

$$Imported\ Steam\ Improvement = \frac{(m_{import,post} - m_{import,baseline}) \times H_{import}}{E_{import}} \qquad Eqn.\ 10$$

$$Imported\ Power\ Improvement = \frac{(Power_{IMP,post} - Power_{IMP,baseline})}{E_{P,import}} \qquad Eqn.\ 11$$

$$Annual\ energy\ savings = Energy\ performance\ improvement \times Op\ hrs \qquad Eqn.\ 12$$

$$Annual\ cost\ savings = [Fired\ Fuel\ Improvement \times Fuel\ cost + (m_{import,post} - m_{import,baseline})\ x\ Steam\ Cost + (Power_{IMP,post} - Power_{IMP,baseline}) \times Power\ Cost] \times\ Op\ hrs \qquad Eqn.\ 13$$

Where:

Fired Fuel Improvement	:	Difference between post-implementation and baseline fuel fired rate (kJ/h)
Imported Steam Improvement	:	Difference between post-implementation and baseline imported steam heat (kJ/h)
Imported Power Improvement	:	Difference between post-implementation and baseline imported power (kJ/h)
Op hrs	:	Number of operating hours in a year (hrs/yr)
Energy performance improvement	:	Energy performance improvement compared to baseline (kJ/h)

Annual energy savings	:	Energy saved in a year (kJ/yr)
Fuel cost	:	Cost of fuel (SGD/kJ)
Steam cost	:	Cost of imported steam (SGD/kg)
Power cost	:	Cost of imported power (SGD/kJ)
Annual cost savings	:	Cost savings in a year (SGD/yr)

5 Typical Scenarios Applicable to Cogeneration Systems

Generally, energy performance improvements in a cogeneration system can be achieved by:

- Increasing HRSG steam production by switching steam production from boilers to the HRSGs
- Maximising GTG power output
- Using the most efficient steam turbines for power production
- Switching from fired heat to steam use in downstream processes
- Switching steam use from higher to lower pressure in downstream processes
- Changes in steam consumption requirement

Increasing HRSG steam production

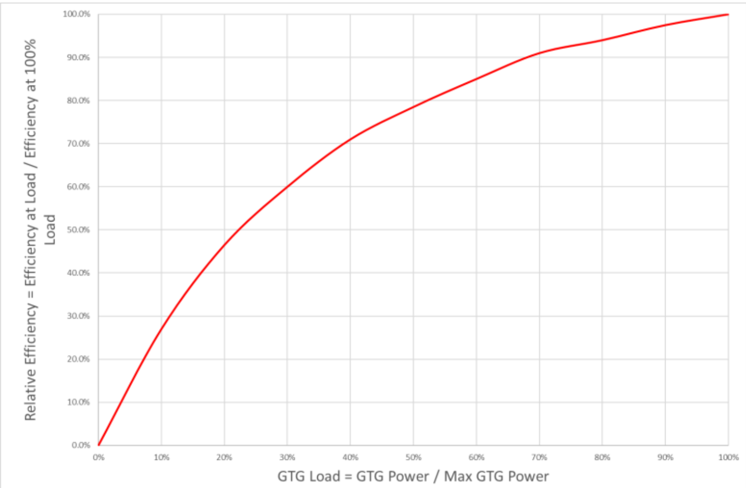
If a HRSG is supplementary firing, this firing is typically at an efficiency of 100% because the exhaust from the GTG is hot and contains a significant quantity of oxygen (typically 14 to 15%). It is, therefore, more efficient to maximise steam production from a fired HRSG.

If a HRSG is not at maximum fuel firing, increasing the supplementary fuel should result in a reduction in stack temperature and stack oxygen.

This can be tracked by monitoring fuel consumption to the HRSGs and boilers.

Maximising GTG power output

The efficiency of a GTG drops as the power output decreases. The figure below shows a typical efficiency curve for a GTG.



Increasing GTG power output will increase fuel firing to the GTG but will lead to:

- reduced fuel consumption in the HRSG,

- or increased steam production from the HRSG to reduce boiler fuel consumption, and reduced power import.

Maximising use of most efficient steam turbines

If multiple steam turbines are being used to generate electrical power then maximising generation from the machines with the highest isentropic efficiency will result in an energy performance improvement.

In addition, increasing the power output from a turbine will increase its isentropic efficiency. For example, if a site is running two machines at 50% load, shutting down one machine to operate only one at 100% can result in energy performance improvement.

This increase can either be used to:

- reduce imported power,
- or reduce steam flow to the condensing section of a turbine, to reduce energy lost in the steam condenser. This will result in a fuel saving in the boilers/HRSG.

Switching from fired heat to steam use

If a HRSG is supplementary fired, and there is room to increase fuel firing, then switching a furnace (fired heater) in a downstream process to steam can result in energy performance improvement as the HRSG fuel firing will have an incremental efficiency of 100%, which is higher than can be achieved in a furnace.

This can be tracked by monitoring fuel consumption in the furnace, HRSGs and boilers.

Switching steam use from higher to lower pressure

If steam turbines are being used to generate electrical power that have extraction at different pressure levels, switching a downstream user from a higher to a lower pressure can increase power generation from the turbine. This increase can either be used to:

- reduce imported power,
- or reduce steam flow to the condensing section of a turbine, to reduce energy lost in the steam condenser. This will result in a fuel saving in the boilers/HRSG.

Changes in the steam consumption requirements

Changes to steam consumption demand can be a result of increased process to process heat recovery, changes to process operations or product slates. These changes can be observed through supply steam flow, condensate recovery and an assessment of the steam users.

6 Instrumentation Requirements

The following section describes the list of critical parameters that should be measured using permanent instruments. The availability of these data will allow for continuous monitoring of cogeneration system efficiency.

- Fuel system
  - Fuel flow to each individual GTG, HRSG, and boiler
- HRSG
  - Stack temperature
  - Stack oxygen content
- Boiler
  - Stack temperature
  - Stack oxygen content
- Steam (HRSG, boiler, import from outside sources)
  - Steam flow rate to users
  - Steam temperature and pressure
- BFW
  - BFW flow rate
  - BFW supply temperature
  - Condensate flow rate
  - Condensate return temperature
- Pump
  - Power

Other parameters such as the enthalpy values of steam and BFW, and the lower heating value of the fuel can be obtained from thermodynamics database or laboratory test results.

As per NEA guidelines, a 2-weeks measurement period is used when calculating the baseline or post-implementation heating system efficiency. The resolution of the collected data should be at least on an hourly basis.