Heating Systems Study

Assessment Framework for Heating Systems

KBR | ENERGY SOLUTIONS | CONSULTING

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Contents

1 Preface

An Assessment Framework ("AF") for each type of Heating System has been developed as part of the requirement specifications of the National Environment Agency (NEA) study. The aim of this study is to analyse the energy performance of heating systems in oil refining, petrochemical and chemical plants. The intention of the AF is to assess the energy performance of the heating systems in operational use by oil refining, petrochemical and chemical plants. The AF will also assess other areas that directly affect the energy performance of Heating Systems (e.g. end-users of energy commodities, pre-heat, process heating, potential for heat integration and waste heat recovery) to optimise process and heat integration.

1.1 Objectives of this Document

The objective of this AF document is to provide the following information:

- Methodology to assess the energy use and performance of Heating Systems in oil refining, petrochemical and chemical plants, as well as other areas that directly affect the energy performance of Heating Systems to optimise process and heat integration to reduce the energy consumption of these systems. The proposed methodology includes the conduct of an energy and mass balance of the Heating Systems and other areas that directly affect their energy performance. The proposed methodology will also assess the breakdown of demand for Energy Commodities by end users.
- A set of energy performance metrics ("Metrics"), including thermal efficiency for each system, to assess the energy performance of each type of Heating System as well as other areas that directly affect the energy performance of Heating Systems to optimise process and heat integration to reduce the energy consumption of these systems. For each Metric, the AF provides a definition, formula, and performance benchmark based on BAT or other benchmarks of best practice. The AF also explains the significance of the Metric, how to interpret it, and the potential energy performance improvement opportunities that can be inferred from applying the Metric to benchmark the energy performance of the Heating Systems against BAT or other best practice.
- A list of necessary data and information for computing the Metrics and identifying performance gaps, together with accompanying descriptions of the data and information required.
- A list of recommended tools, instrumentation, and measurement methods and techniques for data measurement, collection and reporting for each type of Heating System.
- A compilation of spreadsheet templates (or other suitable documentation) for data and information collection and for computing the Metrics for each type of Heating System.

2 Introduction

According to the Department of Statistics Singapore, Singapore's industry (manufacturing) sector is an important contributor to economic growth and was responsible for 21.9%[1] of Singapore's gross domestic product in 2018. Major industries include refining, petrochemical, specialty chemicals, pharmaceuticals, and semiconductors. The Energy Market Authority has estimated that the industrial-related sector accounted for 89.1% (or 55 047 TJ) of total natural gas (NG) consumption and 42.5% (or 21.5 TWh) of all electricity in 2018[2].

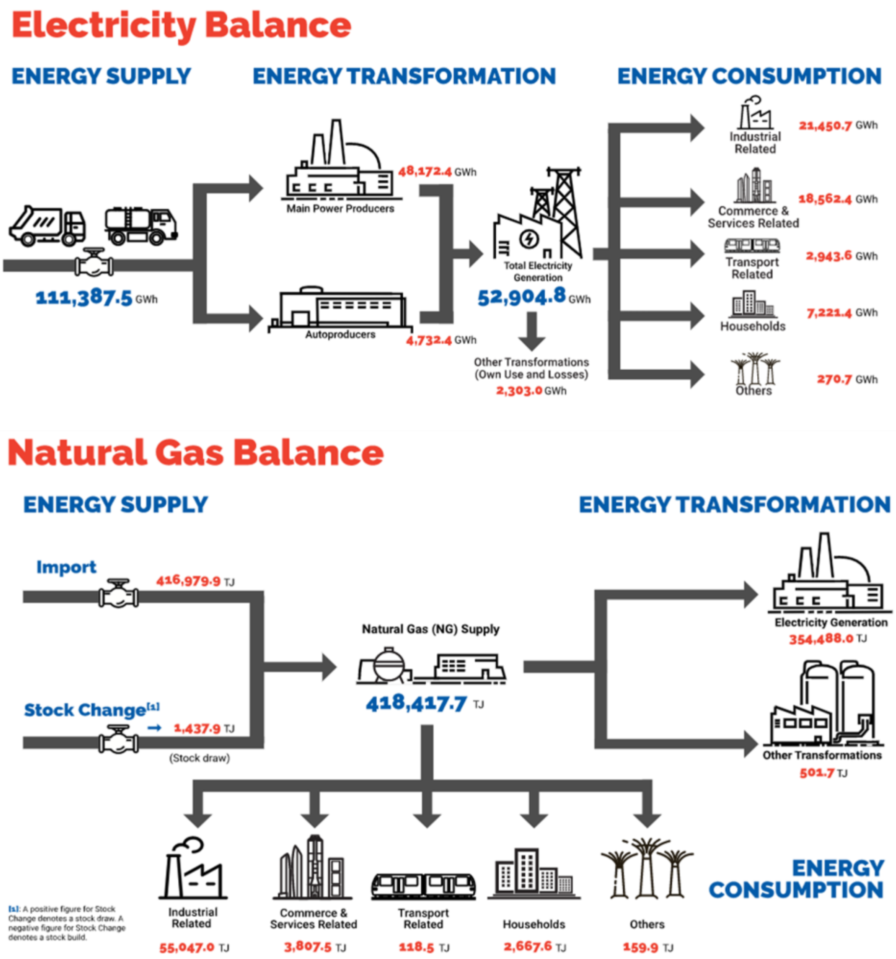


Figure 1: 2018 Electricity and Natural Gas Usage in Singapore[2]

NEA Heating System Study Assessment Framework

Today, energy efficiency is a focal point for governments and society. In addition to reducing operating cost and increasing margin for the industrial sector, energy efficiency improvement represents an important opportunity for Singapore to further reduce emissions and improving industrial competitiveness.

Oil refining, petrochemical and chemical plants account for bulk of energy use in the industrial sector in Singapore. According to the NEA, heating systems alone account for about 95.7%[3] of the energy consumption for these plants. The breakdown of the energy consumption shows the greater emphasis should be placed on direct and indirect heating systems and cogeneration.

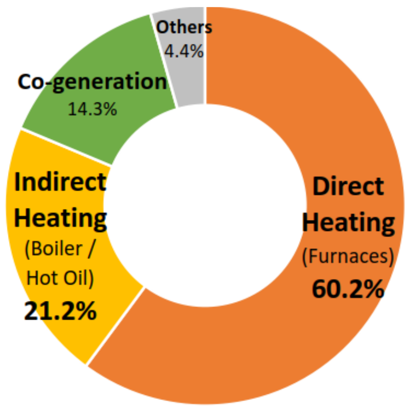


Figure 2: Energy use distribution[3]

Improving the energy performance of these heating systems could potentially lead to significant energy savings and abatement of greenhouse gas emissions for Singapore.

This document details the **Assessment Framework (AF) for Heating Systems**, as part of the NEA energy performance study for the oil refining, petrochemical and chemical plants. The following sections will be covered in this document.

- Methodology to assess the energy use and performance of Heating Systems
- Relevant energy performance metrics
- Information required to compute the metrics and identifying performance gaps
- Recommended tools, instrumentation, and measurement methods and techniques for data measurement, collection and reporting

3 Assessment Framework for Furnaces (Fired Heaters)

The objective of a furnace is to either increase the temperature of a process stream to a target temperature (e.g. before sending it to a fractionator such as in the Atmospheric Crude Distillation or to provide the required reboiling duty as in the BTX unit), a reaction system (e.g. Hydrotreating Process); or provide enough heat for an endothermic reaction to take place (e.g. Ethane Cracker Unit).

3.1 Assessment Methodology

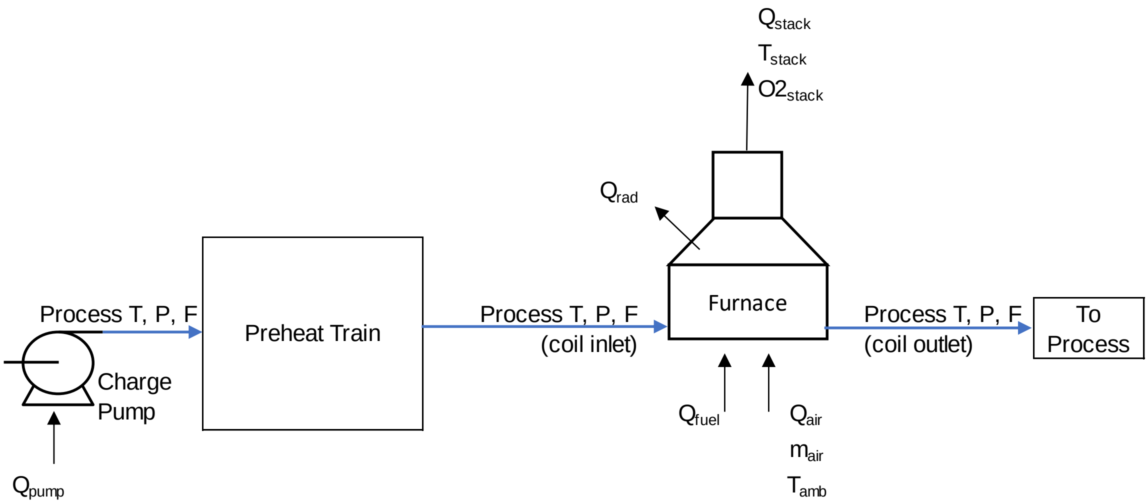


Figure 3: Main considerations for assessing the performance of furnace systems

This Furnace Assessment Methodology covers process furnaces and incinerators. Components associated to a furnace system are:

- The furnace itself, where the temperature of the process stream is raised to the desired level
- Preheat train, where the process stream is heated up before being sent to the furnace. This does not apply to systems where the furnace is used as reboiler on a distillation column.
- Charge pump, where process fluid is pumped through the pre-heat train and the furnace tubes

Main considerations for assess the system's performance are illustrated below. The energy input into a furnace system consists of:

- Fuel provided to the furnace

- Heat from the ambient (combustion) air, which is usually considered negligible and accounted when calculating the stack losses
- Electrical energy used to drive the pump(s)

Of these, the fuel consumption is usually significantly higher than the energy used by the pumps. Thus, fuel consumption is the main parameter to track when looking at energy efficiency of a hot oil system.

The fuel consumption of the furnace can be reduced by increasing the temperature of the combustion air, either by using the stack gases of the furnace itself or by heating with external heat source, for example steam or process waste heat. If the air is preheated using an external heat source, this should be considered as additional heat input to the furnace.

It should be noted that any energy input into the preheat train and the charge pump will affect the inlet temperature of the process stream going into the furnace, and thus affect the heat duty requirement (load) of the furnace. It does not affect the efficiency of the furnace itself. Improving heat recovery in the process itself will have the most significant impact on reducing furnace load.

The energy output in the system shown in Figure 3 consists of:

- Heat transferred to the process stream in the radiant/convection zone and other streams heated in the convection zone (e.g. BFW)
- Furnace losses consisting of heat lost to the stack gases (these are a function of the stack gas temperature and excess oxygen) and radiation losses which are a function of the furnace design. Radiation losses are usually fixed and do not vary with the amount of fuel used by the furnace.
- Insulation losses which are a function of the pipe length, pipe diameter and insulation

To reduce energy consumption at the furnaces, there are 2 key approaches:

1. Maximise furnace thermal efficiency

Furnace thermal efficiency can be maximised by reducing heat losses to the atmosphere. The major heat loss is through the stack flue gas stream. Parameters such as the stack excess oxygen content and stack temperature will heavily influence the amount of heat lost to the atmosphere.

2. Minimise the furnace load

In minimizing furnace load, an assessment of the preheat train will be necessary. The following approach may be taken

    - Pinch analysis to identify opportunities for heat recovery to maximise the coil inlet temperature to the furnace

Minimising the furnace load may lead to a lower thermal efficiency especially when the furnace is near minimum turndown operations. However, the overall energy performance of unit will improve as long as the furnace load reduction is achieved through improved heat integration.

3.2 Energy Performance Metrics

The following table shows a list of metrics for monitoring of a furnace system and the method for calculating the metric.

Table 1: **Recommended Energy Metrics for Furnaces**

Energy System	Hierarchy	Metric	Method
Furnace equipment only	Energy performance indicator	Thermal efficiency (%)	Calculated
	Energy performance indicator	Energy performance gap (Gcal/h)	Calculated
	Energy influencing variable	Stack temperature (°C)	Measured
	Energy influencing variable	Stack oxygen (%)	Measured
Furnace preheat train	Energy performance indicator	Charge pump specific energy consumption (kW/unit throughput)	Calculated
	Energy influencing variable	Coil inlet temperature (°C)	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.

1. Thermal efficiency

The thermal efficiency of the furnace (assuming no radiation losses) can be derived from the heat lost to the furnace stack, which is a function of the stack temperature and the excess oxygen. This can be determined by rigorous heat balance calculations, which can be difficult to perform as detailed composition data for inlet air, fuel and stack gases for a particular furnace is required. A simpler alternative is to use an empirical equation, with constants derived from rigorous heat balance calculations. The thermal efficiency of a furnace, without accounting for radiation losses, can be computed by the following formula.

$$\mathrm{E}_{stack} = 1 - (\mathrm{aO}^3 + \mathrm{bO}^2 + \mathrm{cO} + \mathrm{d}) - (\mathrm{eO}^3 + \mathrm{fO}^2 + \mathrm{gO} + \mathrm{h}) \times (\mathrm{T}_{stack} - \mathrm{T}_{air})$$

Eqn. 1

Where:

E_{stack}	:	Efficiency of furnace without accounting for radiation losses (%)
O	:	Excess oxygen content of stack gases on a dry basis (mole %)
T_{stack}	:	Temperature of stack gases (°C)
T_{air}	:	Temperature of inlet air (°C)
a, b, c, d, e, f, g, h:		Empirical constants derived from rigorous heat balance calculations

Figure 4 below shows a comparison between the efficiency of a furnace using a rigorous heat balance method and the KBR proposed empirical equation, as shown by Eqn. 1. Figure 4 is derived by curve fitting the results of the rigorous calculation method. This shows that the simple empirical equation can give an accurate representation of the efficiency across a large range of stack temperature. Similar charts have been plotted to ascertain that the derived empirical coefficients are also valid across a large range of stack oxygen content.

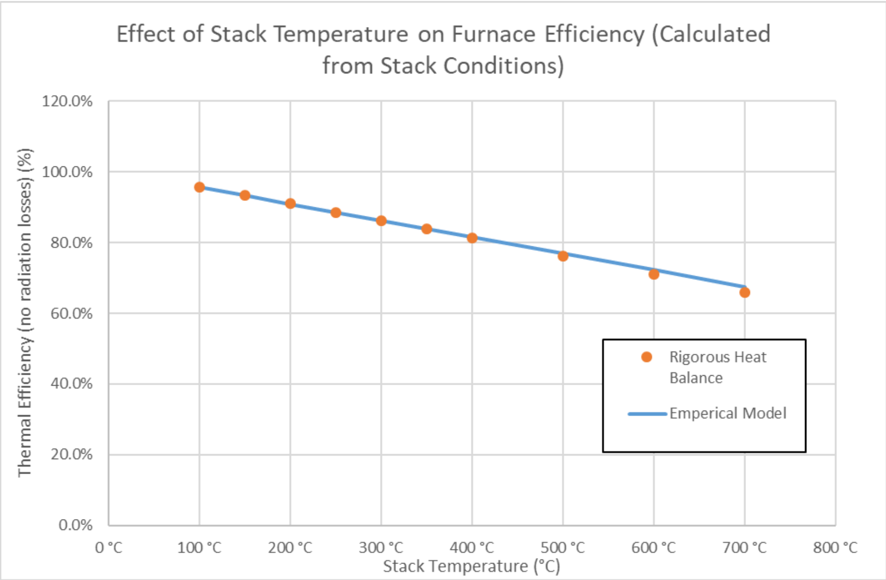


Figure 4: Comparison of two different methods of furnace efficiency calculation

Eqn. 1 does not consider the radiation losses of the furnace. These need to be accounted for, when calculating the thermal efficiency using the following method.

The furnace thermal efficiency can be computed by the following formula:

$$E_{furnace} = E_{stack} - Q_{rad} \qquad \textit{Eqn. 2}$$

Where:

$E_{furnace}$	:	Efficiency of furnace (%)
Q_{rad}	:	Radiation losses (%)

There may be cases where the above method cannot be used due to inaccurate or the lack of instrumentation. An alternative method detailed below can be used to determine the thermal efficiency of furnaces.

$$Heat\ Input = m_{fuel}\ X\ LHV_{fuel} \qquad \text{Eqn. 3}$$

$$Useful\ Heat\ Output = m_{process}\ X\ C_p\ X\ (COT - CIT) \qquad \text{Eqn. 4}$$

$$E_{furnace} = \frac{Useful\ Heat\ Output}{Heat\ Input}\ X\ 100 \qquad \text{Eqn. 5}$$

Where:

$E_{furnace}$	:	Thermal efficiency of furnace (%)
Heat input	:	Fired duty of furnace (MJ/h)
Useful heat output	:	Useful heat absorbed by process stream (MJ/h)
m_{fuel}	:	Mass flow rate of fuel (t/h)
LHV_{fuel}	:	Lower heating value of fuel (kJ/kg)
$m_{process}$	:	Mass flow rate of process stream (t/h)
C_p	:	Specific heat capacity of process stream (kJ/kg.°C)
CIT, COT	:	Furnace coil inlet and outlet temperatures (°C)

Best practice furnace thermal efficiency (BP_{eff}) is at 92%[4]. For ethylene cracker furnaces, BP_{eff} is at 94%[5]. This assumes natural gas or clean fuel gas is burnt.

To reduce furnace load will require an assessment of the preheat train to see if there are opportunities for maximising heat recovery.

Note 1: If the furnace has an air preheater that uses an external heat source, the heat duty of the preheater should be included as heat input into the furnace and so added to Eqn 3. If the air preheater uses stack gases, this is not necessary as the air preheater is recovering energy from the furnace itself.

Note 2: This method will not apply to ethylene cracker furnaces due to its complexity involving numerous material streams. Properties of cracker furnace feed undergo significant changes in the furnace coils, resulting in difficulties in performing heat and mass balance. For ethylene crackers, it is advisable to calculate efficiency using the empirical formula.

2. Energy performance gap

The efficiency and energy gap compared to a best practice furnace can be computed by the following formula:

$$Furnace\ efficiency\ gap\ (\%) = BP_{eff} - E_{furnace} \qquad \textit{Eqn. 6}$$

$$Energy\ gap\ (MJ/h) = \frac{Useful\ Heat\ Output}{E_{furnace}} - \frac{Useful\ Heat\ Output}{BP_{eff}} \qquad \textit{Eqn. 7}$$

3. Stack temperature (°C)

Air fed into the heater supports the combustion process and turns into hot waste gases that is discharged into the atmosphere as flue gas. Flue gas contain significant amounts of heat that can potentially be recovered for combustion air pre-heat to reduce the fuel firing at the heater.

The stack temperature is the measured temperature of the flue gas that exits into the atmosphere. This temperature measurement should be taken after the economizer or any stack heat recovery exchanger to ensure that existing heat recovery measures have been accounted.

Process furnaces designed following best practice will achieve a stack temperature of about 150°C[4] assuming natural gas or clean fuel gas is burnt.

For *ethylene furnaces*, best practice stack temperature can be as low as 110°C[5] with the use of clean fuels. While for *incinerators*, the upper stack temperature should target ~200°C[4] to avoid dew point.

The absence of heat recovery from stack flue gas will lead to a significant loss of waste heat, while excessive heat recovery from stack flue gas may lead to acid condensation, resulting in corrosion of the stack metal.

The acid dew point of the stack temperature is directly correlated with the sulphur content of the fuel. Stack temperature has to be kept higher than the acid dew point temperature to avoid corrosion of the stack.

4. Stack oxygen (%)

The fuel combustion process requires a stoichiometric amount of air, which depends on the fuel type. In practice, excess air must be supplied to ensure complete combustion. However, excessive air flowing through the furnace will lead to unnecessary energy losses. Stack oxygen content is a strong indicator of excessive air, which can potentially be optimised for energy savings.

Best practice stack oxygen content for *process furnaces* ranges between 2.0 to 3.0%[4]. For *ethylene furnaces*, best practice stack oxygen content is 1.5%[5] as these usually come with advanced control of furnace stack oxygen.

It should be noted that positioning of the oxygen analyser will strongly influence the accuracy of this reading as there is a potential for outside air ingress. The ideal location of the stack oxygen analyser should be at the radiant section or the bridge wall of the furnace.

5. Coil inlet temperature (°C)

The coil inlet temperature (CIT) is an indicator of the furnace load. In order to minimise furnace load, CIT will have to be maximised. This can be achieved through the optimization of the pre-heat train using pinch analysis approach.

6. Charge pump specific energy consumption

In some heating systems, the energy consumption of the charge pump may be significant. The specific energy consumption (SEC) of the pump can be monitored to ensure that potential for energy saving can be easily identified.

Changes to the pump SEC may occur if there are significant and prolonged changes to the plant operations, design or loading. Hence, pump SEC should be monitored over the long term for significant changes. This can provide indications that energy saving projects on the pump application may become viable if SEC increases significantly permanently or for prolonged periods of time.

There is no standard benchmark for pump SEC as it is heavily dependent on its application, pump design, system pressure, fluid properties etc.

3.3 Monitoring of Improvements

Monitoring of the improvements in the system should be done by:

- Tracking thermal efficiency of furnace
    - A reduction in stack temperature and stack oxygen will improve furnace efficiency. Reducing stack oxygen will result in a lower air flow through the furnace and reduce the heat lost to the stack accordingly.
- Tracking specific fuel consumption in the furnace

  - This will reduce if the furnace efficiency improves. To minimise the effect of non-energy performance parameters such as unit throughput, fuel consumption should be seeing as energy consumed per unit of throughput or product generated.
- Tracking the coil inlet temperature to monitor the performance of the pre-heat train prior to furnace heating.

3.4 Data Requirements

The following information is required to carry out a comprehensive analysis the performance and revamp options of a furnace.

Plant Measurements:

- Fuel analysis (type, flow rate, temperature, lower heating value)
- Flue gas analysis (including stack temperature and stack oxygen)
- Process stream conditions (flows, specific heat capacity, coil inlet (CIT) and outlet (COT) temperature)
- Combustion air inlet temperature
- Combustion air temperature after air preheater (if available)
- Complete operating data of furnace peripherals such as waste heat recovery units and fans
- Pump parameters (power, process flow)
- Combustion air temperature

Datasheets:

- Furnace specification document (design data, process stream conditions)
- Furnace inspection report
- Charge pump datasheet

4 Assessment Framework for Hot Oil Systems

The objective of a hot oil system is to provide heat to various processes through a centralised system (i.e. fired heater) where the heating medium is a hydrocarbon stream (defined as hot oil).

4.1 Assessment Methodology

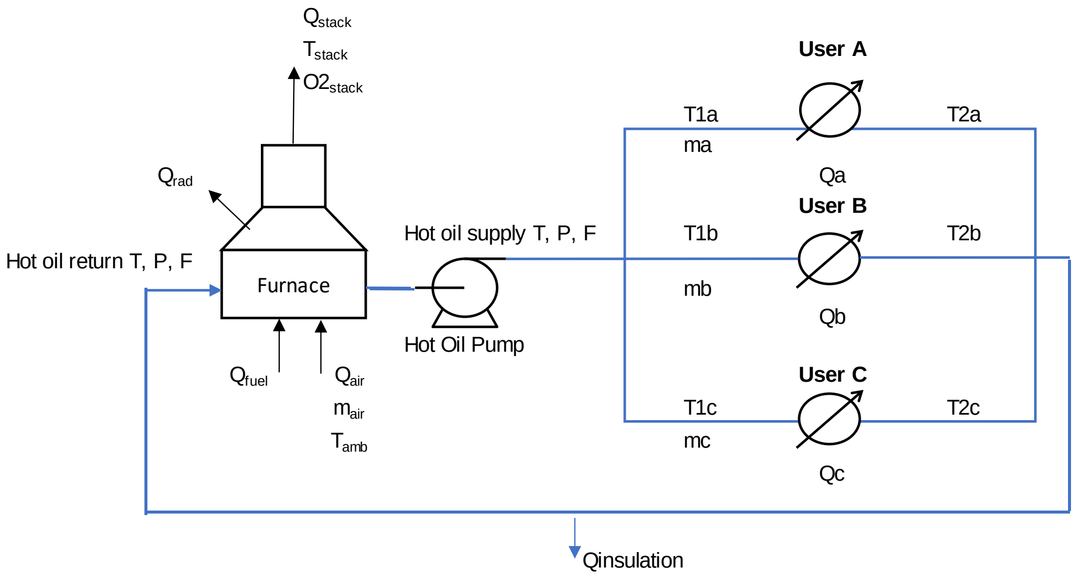


Figure 5: Main considerations for assessing the performance of hot oil systems

A hot oil system usually comprises:

- Heater(s) to raise the temperature of the oil to the temperature required by the end users
- Pump(s) to transfer the oil to the end users
- Heat exchangers to transfer the energy to the end users

Figure 5 shows a simple schematic of a typical hot oil system. In this example, the oil is heated to a target supply temperature, in the heater before being pumped to three end users, and then returned to the heater at a return temperature.

The energy input to a hot oil system consists of:

- Fuel provided to the hot oil heater
- Heat from the ambient (combustion) air, which is usually considered negligible and accounted when calculating the stack losses

- Electrical energy used to drive the pump(s)

Of these, the fuel consumption is usually significantly higher than the energy used by the pumps. Thus, fuel consumption is the main parameter to track when looking at energy efficiency of a hot oil system.

The fuel consumption of the heater can be reduced by increasing the temperature of the combustion air, either by using the stack gases of the heater itself or by heating with external heat source, for example steam or process waste heat. If the air is preheated using an external heat source, this should be considered as additional heat input to the heater.

The energy output in the system shown in Figure 5 consists of:

- Heat transferred to the end users. All this energy is considered to be usefully used by the end users
- Heater losses consisting of heat lost to the stack gases (these are a function of the stack gas temperature and excess oxygen), conductive and radiation losses which are a function of the heater design. Radiation losses are usually fixed and do not vary with the amount of fuel used by the heater. On a well-maintained heater, losses by heat conduction through the refractory or ceramic fibre insulated walls are quite small.
- Insulation losses which are a function of the pipe length, pipe diameter and insulation.

To reduce energy consumption in a hot oil system, there are 2 key approaches:

1. Maximise heater thermal efficiency

   Heater thermal efficiency can be maximised by reducing heat losses to the atmosphere. The major heat loss is through the stack flue gas stream. Parameters such as the stack excess oxygen content and stack temperature will heavily influence the amount of heat lost to the atmosphere.

2. Minimise the heater load

   In minimizing heater load, an assessment of the hot oil users will be necessary. The following approaches may be taken:

   - Pinch analysis to identify opportunities for heat recovery to reduce usage of hot oil
   - Optimise hot oil consuming processes such as distillation columns

Minimising the heater load may lead to a lower thermal efficiency especially when the heater is near minimum turndown operations. However, the overall energy performance of unit will improve as long as the heater load reduction is achieved through improved heat integration.

4.2 Energy Performance Metrics

The following table shows a list of metrics for monitoring of a hot oil system and the method for calculating the metric.

Table 2: Recommended energy metrics for hot oil heaters

Energy System	Hierarchy	Metric	Method
Heater equipment only	Energy performance indicator	Thermal efficiency (%)	Calculated
	Energy performance indicator	Energy performance gap (Gcal/h)	Calculated
	Energy influencing variable	Stack temperature (°C)	Measured
	Energy influencing variable	Stack oxygen (%)	Measured
	Energy influencing variable	Hot oil supply temperature (°C)	Measured
	Energy influencing variable	Hot oil return temperature (°C)	Measured
Hot oil system	Energy performance indicator	Overall mass / energy balance of hot oil system	Calculated
	Energy performance indicator	Hot oil pump specific energy consumption (kW/unit throughput)	Calculated

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.

1. Thermal efficiency

The thermal efficiency of the heater (assuming no radiation losses) can be derived from the heat lost to the heater stack, which is a function of the stack temperature and the excess oxygen. This can be determined by rigorous heat balance calculations, which can be difficult to perform as detailed composition data for inlet air, fuel and stack gases for a particular heater is required. A simpler alternative is to use an empirical equation, with constants derived from rigorous heat balance calculations. The thermal efficiency of a heater, without accounting for radiation losses, can be computed by the following formula.

$$E_{stack} = 1 - (aO^3 + bO^2 + cO + d) - (eO^3 + fO^2 + gO + h) \text{ x } (T_{stack} - T_{air})$$

Eqn. 8

Where:

E_{stack} : Efficiency of heater without accounting for radiation losses (%)

O	:	Excess oxygen content of stack gases on a dry basis (mole %)
T_{stack}	:	Temperature of stack gases (°C)
T_{air}	:	Temperature of inlet air (°C)
a, b, c, d, e, f, g, h	:	Empirical constants derived from rigorous heat balance calculations

Figure 6 below shows a comparison between the efficiency of a heater using a rigorous heat balance method and the KBR empirical equation, as shown by Eqn. 8. Figure 6 is derived by curve fitting the results of the rigorous calculation method. This shows that the simple empirical equation can give an accurate representation of the efficiency across a large range of stack temperature. Similar charts have been plotted to ascertain that the derived empirical coefficients are also valid across a large range of stack oxygen content.

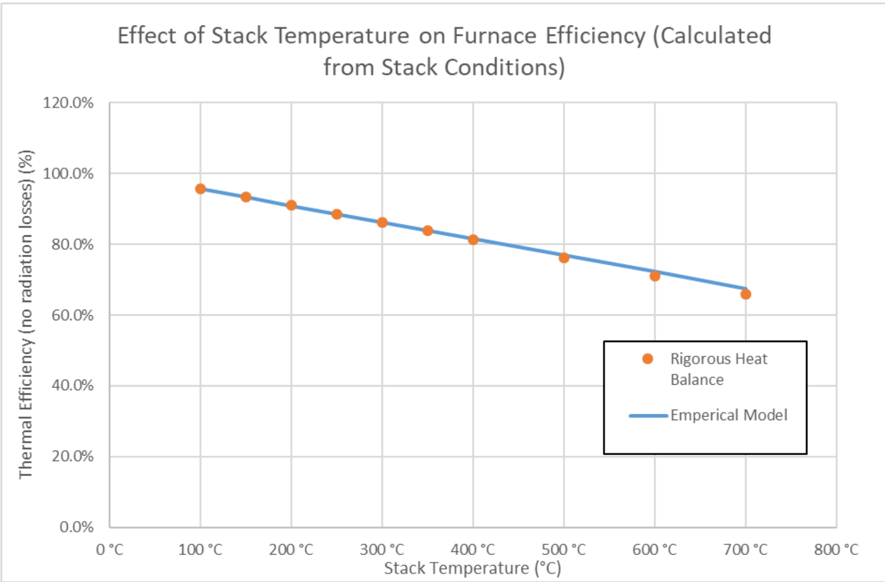


Figure 6: **Comparison of two different methods of heater efficiency calculation**

Eqn. 8 does not consider the radiation losses of the heater. These need to be accounted for, when calculating the thermal efficiency using the following method.

The heater thermal efficiency can be computed by the following formula:

$$E_{heater} = E_{stack} - Q_{rad} \qquad \textit{Eqn. 9}$$

Where:

E_{heater} : Efficiency of heater (%)

Q_{rad}	:	Radiation losses (%)

There may be cases where the above method cannot be used due to inaccurate or the lack of instrumentation. An alternative method can be used to determine the thermal efficiency of heaters using data from the hot oil loop.

$$Heat\ Input = m_{fuel}\ X\ LHV_{fuel} \qquad \text{Eqn. 10}$$

$$Useful\ Heat\ Output = m_{hot\ oil}\ X\ C_{p,avg}\ X\ (T_{supply} - T_{return}) \qquad \text{Eqn. 11}$$

$$E_{hot\ oil\ heater} = \frac{Useful\ Heat\ Output}{Heat\ Input}\ X\ 100 \qquad \text{Eqn. 12}$$

Where:

$E_{hot\ oil\ heater}$	:	Thermal efficiency of hot oil heater (%)
Heat input	:	Fired duty of heater (MJ/h)
Useful heat output	:	Useful heat absorbed by hot oil (MJ/h)
m_{fuel}	:	Mass flow rate of fuel (t/h)
LHV_{fuel}	:	Lower heating value of fuel (kJ/kg)
$m_{hot\ oil}$	:	Mass flow rate of hot oil stream (t/h)
C_p	:	Specific heat capacity of hot oil stream (kJ/kg.°C)
T_{supply}, T_{return}	:	Hot oil supply and return temperatures (°C)

To reduce heater load will require an assessment of the end users to see if there is scope to reduce hot oil use by improving heat recovery and by making process changes.

Note: If the heater has an air preheater that uses an external heat source, the heat duty of the preheater should be included as heat input into the heater and so added to Eqn 10. If the air preheater uses stack gases, this is not necessary as the air preheater is recovering energy from the heater itself.

2. Energy performance gap

Best practice heater efficiency (BP_{eff}) is at 92%[4], assuming natural gas or clean fuel gas is burnt. [KBR standards and specifications for furnace/fired heaters design/performance]. The efficiency and energy gap compared to a best practice heater can be computed by the following formula:

$$Furnace\ efficiency\ gap\ (\%) = BP_{eff} - E_{hot\ oil\ heater} \qquad \text{Eqn. 13}$$

$$Energy\ gap\ (MJ/h) = \frac{Useful\ Heat\ Output}{E_{hot\ oil\ heater}} - \frac{Useful\ Heat\ Output}{BP_{eff}} \qquad \text{Eqn. 14}$$

3. Stack temperature (°C)

Air fed into the heater supports the combustion process and turns into hot waste gases that is discharged into the atmosphere as flue gas. Flue gas contain significant amounts of heat that can potentially be recovered for combustion air pre-heat to reduce the fuel firing at the heater.

The stack temperature is the measured temperature of the flue gas that exits into the atmosphere. This temperature measurement should be taken after the economizer or any stack heat recovery exchanger to ensure that existing heat recovery measures have been accounted for.

Process heaters designed following best practice will achieve a stack temperature of about 150°C[4], assuming natural gas or clean fuel gas is burnt.

The absence of heat recovery from stack flue gas will lead to a significant loss of waste heat, while excessive heat recovery from stack flue gas may lead to acid condensation, resulting in corrosion of the stack metal.

The acid dew point of the stack temperature is directly correlated with the sulphur content of the fuel. Stack temperature has to be kept higher than the acid dew point temperature to avoid corrosion of the stack.

4. Stack oxygen (%)

The fuel combustion process requires a stoichiometric amount of air, which depends on the fuel type. In practice, excess air must be supplied to ensure complete combustion. However, excessive air flowing through the heater will lead to unnecessary energy losses. Stack oxygen content is a strong indicator of excessive air, which can potentially be optimised for energy savings.

Best practice stack oxygen content is 2.0 to 3.0%[4]. Advanced control of heater stack oxygen content will allow for a lower stack oxygen content.

It should be noted that positioning of the oxygen analyser will strongly influence the accuracy of this reading as there is a potential for outside air ingress. The ideal location of the stack oxygen analyser should be at the radiant section or the bridge wall of the heater.

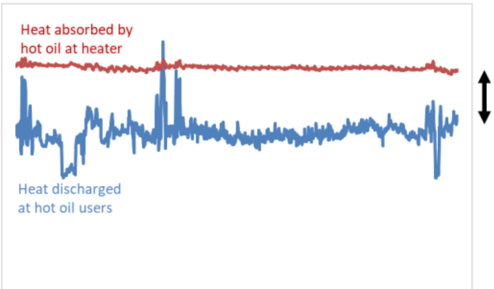
5. Hot oil supply and return temperature

The hot oil system is typically designed for a set temperature difference. The hot oil supply and return temperature serve as an indication of the overall heat load on the hot oil system. A smaller than designed temperature difference indicates a low heat requirement at the end users. This creates opportunities for reducing the flow of hot oil in the loop to reduce electricity consumption by hot oil circulation pump.

6. Overall mass and energy balance of hot oil system

The generation and usage of heat in hot oil at the plant should be accounted for to quantify the gaps in the hot oil system. This accounting will require a comprehensive set of permanent instrumentation. Long-term tracking of the gap between the heat absorbed by hot oil at the heater vs heat discharged at hot oil users may yield insights to the performances of the hot oil system.

An example hot oil heat balance at the heater and users is shown below.



This gap between heat absorption and discharge of hot oil may be attributed to

- Plant upsets, operating modes, product slates
- Deterioration in heat exchangers, insulation
- Instrumentation errors
- Assumptions due to lack of instrumentation
- Weather

Figure 7: Example hot oil system heat balance

Heat losses through pipe insulation does contribute to the gap between hot oil heat absorption and discharge. However, these losses are difficult to quantify, especially when industrial hot oil systems tend to be expansive.

7. Hot oil pump specific energy consumption

In some heating systems, the energy consumption of the hot oil pump may be significant. The specific energy consumption (SEC) of the pump can be monitored to ensure that potential for energy saving can be easily identified.

Changes to the pump SEC may occur if there are significant and prolonged changes to the plant operations, design or loading. Hence, pump SEC should be monitored over the long term for significant changes. This can provide indications that energy saving projects on the pump application may become viable if SEC increases significantly permanently or for prolonged periods of time.

There is no standard benchmark for pump SEC as it is heavily dependent on its application, pump design, system pressure, fluid properties etc.

4.3 Monitoring of Improvements

Monitoring of the improvements in the system should be done by:

- Tracking thermal efficiency of heater
    - A reduction in stack temperature and stack oxygen will improve heater efficiency. Reducing stack oxygen will result in a lower air flow through the heater and reduce the heat lost to the stack accordingly.
- Tracking the hot oil flow, supply and return temperatures as these will provide indications to the overall heat load on the hot oil heater.

4.4 Data Requirements

Where possible, plant measured data should be used. However, not all data is measured so datasheets should be used. The following data are required to determine the heater efficiency and gap to best practice are:

Plant Measurements:

- Fuel analysis (type, flow rate, temperature, lower heating value)
- Flue gas analysis (including stack temperature and stack oxygen)
- Hot oil conditions (flows, supply and return temperatures)
- Hot oil flow to users
- Hot oil user conditions (process stream flows, heat exchanger inlet and outlet temperature, stream composition or specific heat)
- Hot oil pump parameters (power, process flow)
- Combustion air temperature

Datasheets

- Hot oil heater specification document (design data)
- Hot oil heater inspection report
- Physical properties of the hot oil (e.g., specific heat capacity)
- Hot oil pump datasheet

5 Assessment Framework for Boiler Systems

Boilers are defined as vessels or tanks in which heat produced from the combustion of fuels such as natural gas, fuel oil, wood, or coal is used to generate hot water or steam for applications ranging from building space heating to electric power production or industrial process heat.

Expanding on the reach of the boilers, this document (together with the Assessment Framework for Cogeneration Systems) covers different aspects that need to be considered to make a boiler system more efficient.

5.1 Assessment Methodology

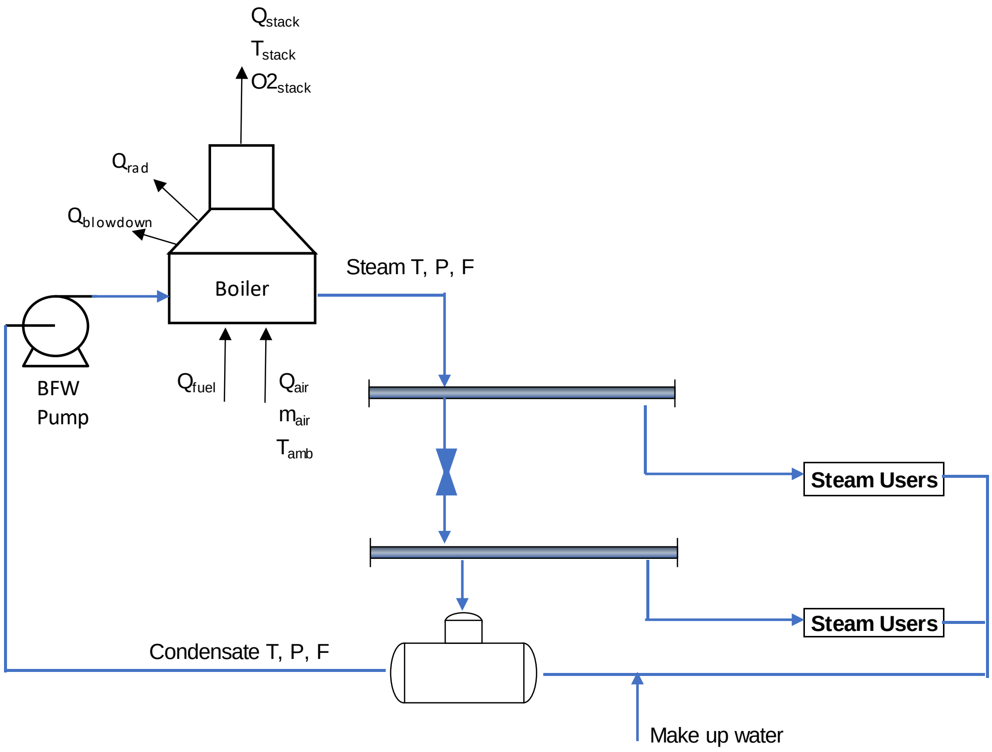


Figure 8: Main considerations for assessing the performance of boiler systems

Boilers are typically major energy consuming systems in an industrial facility. The main components of the system include:

- Boilers, used to fulfil the steam balance
- Pump(s) to transfer the boiler feed water (BFW) from the deaerator to the steam generators
- Deaerator(s) use heat, typically in the form of low pressure steam, to decrease oxygen content in the BFW

- Steam users are divided in three categories
    - Live steam users, where the steam or condensate is not returned, but joins the process stream (e.g. stripping steam)
    - Heating steam users, where the condensate can be returned (e.g. steam sent to distillation column reboiler)
    - Steam turbines, where energy from steam is extracted as shaft work (refer to Cogeneration Assessment Framework)

The energy input to a boiler system consists of:

- Fuel provided to the boiler
- Heat from the ambient (combustion) air, which is usually considered negligible and accounted when calculating the stack losses
- Electrical energy used to drive the pump(s)

Of these, the fuel consumption is usually significantly higher than the energy used by the pumps. Thus, fuel consumption is the main parameter to track when looking at energy efficiency of a boiler system.

The fuel consumption of the boiler can be reduced by increasing the temperature of the combustion air, either by using the stack gases of the boiler itself or by heating with external heat source, for example steam or process waste heat. If the air is preheated using an external heat source, this should be considered as additional heat input to the boiler.

The energy output in the system shown in consists of:

- Steam generated by the boiler
- Boiler losses consisting of heat lost to the stack gases (these are a function of the stack gas temperature and excess oxygen), conductive and radiation losses which are a function of the boiler design. Radiation losses are usually fixed and do not vary with the amount of fuel used by the boiler. On a well-maintained boiler, losses by heat conduction through the refractory or ceramic fibre insulated walls are quite small.
- Insulation losses which are a function of the pipe length, pipe diameter and insulation
- Blowdown flow presents another form of heat loss as hot water is discharged to avoid the accumulation of impurities in the boiler water. Heat lost via blowdown is usually small.

To reduce energy consumption in a boiler system, there are 2 key approaches:

- Maximise boiler efficiency

Boiler thermal efficiency can be maximised by reducing heat losses to the atmosphere. The major heat loss is through the stack flue gas stream. Parameters such as the stack excess oxygen content and stack temperature will heavily influence the amount of heat lost to the atmosphere.

- Minimise boiler load

  In minimizing boiler load, an assessment of the steam users will be necessary. The following approaches may be taken.

  - Pinch analysis to identify opportunities for heat recovery to reduce usage of steam
  - Optimise steam consuming processes such as distillation columns
  - Maximise steam generation from waste heat sources

Minimising the boiler load may lead to a lower thermal efficiency especially when the boiler is near minimum turndown operations. However, the overall energy performance of unit will improve as long as the boiler load reduction is achieved through improved heat integration.

5.2 Energy Performance Metrics

The following table shows a list of metrics for monitoring of a boiler system and the method for calculating the metric.

Table 3: Recommended energy metrics for boiler systems

Energy System	Hierarchy	Metric	Method
Boiler equipment only	Energy performance indicator	Thermal efficiency (%)	Calculated
	Energy performance indicator	Energy performance gap (Gcal/h)	Calculated
	Energy influencing variable	Stack temperature (°C)	Measured
	Energy influencing variable	Stack oxygen (%)	Measured
	Energy influencing variable	Steam flow (t/h)	Measured
General steam and condensate system	Energy performance indicator	Overall mass / energy balance of steam system	Calculated
	Energy performance indicator	BFW pump specific energy consumption (kW/unit throughput)	Calculated
	Energy influencing indicator	Condensate recovery (%)	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.

1. Thermal efficiency

The boiler thermal efficiency can be computed by the following formula.

$$Heat\ Input = m_{fuel}\ X\ LHV_{fuel}$$ Eqn. 15

$$Useful\ Heat\ Output = m_{steam}\ X\ (H_{steam} - H_{BFW})$$ Eqn. 16

$$E_{boiler} = \frac{Useful\ Heat\ Output}{Heat\ Input}\ X\ 100$$ Eqn. 17

In case of waste heat boiler,

$$Heat\ Input = m_{process\ stream}\ X\ C_{p,process\ stream}\ X\ (T_{in} - T_{out})$$ Eqn. 18

Where:

E_{boiler}	:	Thermal efficiency of boiler (%)
Heat input	:	Fired duty of boiler (MJ/h)
Useful heat output	:	Useful heat absorbed by BFW (MJ/h)
m_{fuel}	:	Mass flow rate of fuel (t/h)
m_{steam}	:	Mass flow rate of steam (t/h)
H_{steam}	:	Enthalpy value of steam (kJ/kg)
H_{BFW}	:	Enthalpy value of BFW (kJ/kg)
LHV_{fuel}	:	Lower heating value of fuel (kJ/kg)
$m_{process\ stream}$	:	Mass flow rate of process stream (t/h)
$C_{p\ process\ stream}$	:	Specific heat capacity of process stream (kJ/kg.°C)
T_{in}, T_{out}	:	Process stream inlet and outlet temperatures (°C)

Note: If the boiler has an air preheater that uses an external heat source, the heat duty of the preheater should be included as heat input into the boiler and so added to Eqn 15. If the air preheater uses only stack gases, this is not necessary as the air preheater is recovering energy from the boiler itself.

The thermal efficiency of a boiler can also be calculated using the stack temperature and stack excess oxygen using an empirical formula. The method for doing this is outlined in the Assessment Framework for Furnaces.

2. Energy performance gap

Best practice Boiler efficiency (BP_{eff}) is at 92%[6], assuming natural gas or clean fuel gas is burnt. The efficiency and energy gap compared to a best practice boiler can be computed by the following formula:

$$Boiler\ efficiency\ gap\ \% = BP_{eff} - E_{boiler} \qquad \text{Eqn. 19}$$

$$Energy\ gap = \frac{Useful\ Heat\ Output}{E_{boiler}} - \frac{Useful\ Heat\ Output}{BP_{eff}} \qquad \text{Eqn. 20}$$

3. Stack temperature (°C)

Air fed into the boiler supports the combustion process and turns into hot waste gases that is discharged into the atmosphere as flue gas. Flue gas contain significant amounts of heat that can potentially be recovered for combustion air pre-heat to reduce the fuel firing at the boiler.

The stack temperature is the measured temperature of the flue gas that exits into the atmosphere. This temperature measurement should be taken after the economizer or any stack heat recovery exchanger to ensure that existing heat recovery measures have been accounted for.

Best practice stack temperature is at about 150°C[6] assuming natural gas or clean fuel gas is burnt.

The absence of heat recovery from stack flue gas will lead to a significant loss of waste heat, while excessive heat recovery from stack flue gas may lead to acid condensation, resulting in corrosion of the stack metal.

The acid dew point of the stack temperature is directly correlated with the sulphur content of the fuel. Stack temperature has to be kept higher than the acid dew point temperature to avoid acid condensation.

4. Stack oxygen (%)

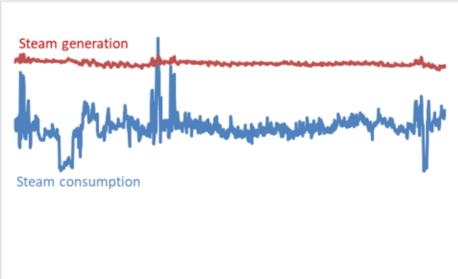
The fuel combustion process requires a stoichiometric amount of air. In practice, excess air must be supplied to ensure complete combustion. However, excessive air flowing through the boiler will lead to unnecessary energy losses. Stack oxygen content is a strong indicator of excessive air, which can potentially be optimised for energy savings.

Best practice stack oxygen content is 2.0 to 3.0%[6]. Advanced control of boiler stack oxygen content will allow for a lower stack oxygen content. It should be noted that positioning of the oxygen analyser will strongly influence the accuracy of this reading as there is a potential for outside air ingress. The ideal location of the stack oxygen analyser should be at the radiant section or the bridge wall of the boiler.

5. Overall mass and energy balance of steam system

The generation and consumption of steam at the plant should be accounted for to quantify the gaps in steam balance. This accounting will require a comprehensive set of permanent instrumentation. Long-term tracking of the gap between total steam generation and consumption may yield insights to the performances of the heating system.

An example of a steam generation and consumption chart is shown below.



This gap between generation & consumption of steam may be attributed to

- Plant upsets, operating modes, product slates
- Deterioration in heat exchangers, insulation
- Site steam losses and leaks (malfunctioning steam traps)
- Instrumentation errors
- Assumptions due to lack of instrumentation
- Weather

Figure 9: Example steam system heat balance

Heat losses through pipe insulation, steam leakages and failed steam trap do contribute to the gap between steam generation and consumption curve. However, these losses are difficult to quantify, especially when industrial steam systems tend to be expansive.

Steam pipe insulation and steam traps should be routinely reviewed for deterioration or failures. Advanced monitoring tools can also be deployed for the condition monitoring of steam traps for timely intervention.

6. BFW pump specific energy consumption

In some heating systems, the energy consumption of the BFW pump may be significant. The specific energy consumption (SEC) of the pump can be monitored to ensure that potential for energy saving can be easily identified.

Changes to the pump SEC may occur if there are significant and prolonged changes to the plant operations, design or loading. Hence, pump SEC should be monitored over the long term for significant changes. This can provide indications that energy saving projects on the pump application may become viable if SEC increases significantly permanently or for prolonged periods of time.

There is no standard benchmark for pump SEC as it is heavily dependent on its application, pump design, system pressure, fluid properties etc.

7. Condensate recovery

Heat is also lost through the discharge of hot condensate that usually comes from heating steam use. The recovery of hot condensate should be maximised whenever possible so that lesser deaeration steam is needed to heat condensate to its saturation temperature. This also helps in reducing the demand for make-up water into the boiler system.

Condensate recovery can be calculated by performing a mass balance around the deaerator.

$$\%\ condensate\ recovery = \frac{m_{condensate\ return}}{m_{BFW\ from\ deaerator}}\ X\ 100 \qquad \text{Eqn. 21}$$

Where:

$m_{condensate\ return}$	:	Mass flow rate of return condensate to deaerator (t/h)
$m_{BFW\ from\ deaerator}$	:	Mass flow rate of BFW from deaerator (t/h)

Eqn. 21 should be modified accordingly depending on the availability and positioning of condensate flowmeters. Flow rate of make-up water to deaerator, if available, can also be used for computation of % condensate recovery.

8. Deaerator pressure

Deaerators typically use low pressure steam to provide heating and stripping of dissolved gases from boiler feed water. As deaerators can operate across a range of pressures, it uses varying amounts of steam. For a simple steam system with no steam turbine, deaerator pressure can be lowered to achieve a lower BFW temperature, enhancing heat recovery at boiler economizer.

The optimization of deaerator pressure becomes more complex in a cogeneration system. Opportunities associated with deaerators are fully dependent on the site steam system.

5.3 Monitoring of Improvements

Monitoring of the improvements in the system should be done by:

- Tracking thermal efficiency of boiler
  - A reduction in stack temperature and stack oxygen will improve boiler efficiency. Reducing stack oxygen will result in a lower air flow through the boiler and reduce the heat lost to the stack accordingly.
- Tracking site steam demand

- Improvement in heat recovery in the plant will lead to an overall reduction in steam demand. However, this may be heavily influenced by process side operations such as changes to product qualities or decoking procedures.

5.4 Data Requirements

Where possible, plant measured data should be used. However, not all data is measured so datasheets should be used. The following data are required to determine the boiler efficiency and gap to best practice.

Plant Measurements:

- Fuel analysis (type, flow rate, temperature, lower heating value)
- BFW temperature and flow
- Steam temperature and pressure
- Steam generation flow (or blowdown rate)
- Boiler stack temperature and oxygen
- Steam demand of users
- BFW pump parameters (power, flow)
- Condensate, BFW and make-up water conditions (temperature, flow)
- Combustion air temperature

  For waste heat boilers
- Process stream properties (specific heat capacity, flow, inlet/outlet temperature)

Datasheets

- Boiler specification document
- Boiler feed water pump datasheet

6 Assessment Framework for Cogeneration Systems

Cogeneration is defined by the U.S. Dept. of Energy as the simultaneous production of electrical or mechanical work and thermal energy from a process, thus reducing the amount of heat or energy lost from the process. This type of arrangement is also known as combined heat and power (CHP).

Expanding on the reach of the boilers, this document (together with the Assessment Framework for Boilers) covers different aspects that need to be considered to make the steam system more efficient.

6.1 Assessment Methodology

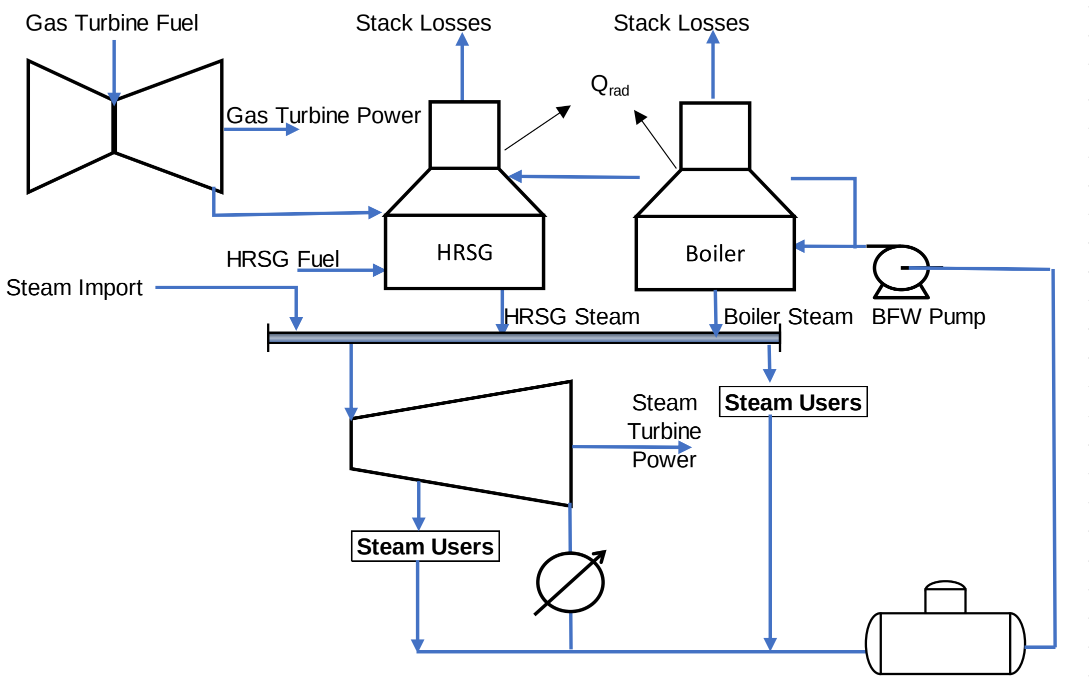


Figure 10: Simplified sketch of a cogeneration system

The main components of a cogeneration system include:

- A gas turbine (GT) to generate shaft work, which is used to generate electrical power
- A heat recovery steam generator (HRSG) to recover energy from the hot GT exhaust. The HRSG is usually used to generate steam (in some instances at multiple pressure levels) and can have burners to fire additional fuel to increase steam production and increase steam temperature.
- Boiler(s) to provide steam to supplement steam production from the HRSG

- Steam import from third party suppliers, again to supplement steam production from the HRSG/boiler
- Steam turbine generator(s) (STG) to generate additional shaft work, and power. The STG can be used to provide steam to end users, by extraction to a lower pressure and to increase power production by condensing the exhaust steam under vacuum
- Pump(s) to transfer the boiling feed water (BFW) from the deaerator to the steam generators
- Deaerator(s) use heat, typically in the form of low pressure steam, to decrease oxygen content in the BFW
- Steam users are divided in three categories
    - Live steam users, where the steam or condensate is not returned, but joins the process stream (e.g. stripping steam)
    - Heating steam users, where the condensate can be returned (e.g. steam sent to distillation column reboiler)
    - Steam turbines, where energy from steam is extracted as shaft work

Figure 10 above shows a simple schematic of a cogeneration system. In this example, steam from the HRSG is sent to a two stage STG with extraction and condensing to provide steam to end users and power. In this case, the HRSG steam is sufficient to provide enough steam for the end users and for the power production from the STG. In situations where the HRSG steam is insufficient, additional steam production may be done by boilers (see Assessment Framework for Boilers).

Some GTGs have water/steam injection to reduce NOx emissions and also to increase power output. Where this is the case, the additional heat input from the water/steam has to be taken into account, as additional GTG fuel.

The energy input into a cogeneration system consists of:

- Fuel provided to the GTG
- Heat content of any water/steam injection into the GTG
- Fuel provided to the HRSG (for supplementary burners, if applicable)
- Fuel to boilers

The energy output in the system shown in the Figure 10 above consists of:

- Power output from the GTG
- Power output from the STG
- Heat (typically in the form of steam) transferred to the end users

- Heat losses consisting of: a) heat lost to the stack gases from the HRSG and boilers, b) radiant losses from the HRSG and boilers, c) losses from the vacuum condenser (if applicable) on the exhaust of the STG, and d) steam losses across the system due to pipework insulation and condensate losses.

  The most significant losses are usually the stack gas losses, heat lost to cooling in the vacuum condenser and condensate losses.

To reduce energy consumption in a cogeneration system, like the one shown above, there are several key approaches.

1. Maximise GTG efficiency
2. Maximise HRSG efficiency
3. Maximise STG efficiency
4. Minimise the heat loss to the vacuum condenser (if applicable)
5. Reduce site power demand
6. Reduce steam demand of end users

There may be situations where economic considerations, rather than energy efficiency, drive the site's operating philosophy when meeting steam and power demand (e.g. power import/export philosophy).

6.2 Energy Performance Metrics

The following table shows a list of metrics for monitoring of a furnace system and the method for calculating the metric.

Table 4: Recommended 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.

1. Overall thermal efficiency of cogeneration system

$$Site\ Power\ Demand = (Power_{GTG} + Power_{STG} + Power_{IMP}) * 3600 \qquad \text{Eqn. 22}$$

$$Site\ Heat\ Demand = m_{steam} X\ H_{steam} - m_{cond}\ X\ H_{cond} \qquad \text{Eqn. 23}$$

Eqn. 23 represents the steam energy supplied to the end users.

$$Fired\ Fuel = (m\ X\ LHV)_{GTG\ fuel} + (m\ X\ LHV)_{HRSG\ fuel} + (m\ X\ LHV)_{boiler\ fuel} \qquad \text{Eqn. 24}$$

$$Imported\ Steam = \frac{m_{import}\ X\ H_{import}}{E_{import}} \qquad \text{Eqn. 25}$$

$$Imported\ Power = \frac{Power_{IMP}}{E_{PIMP}} \qquad \text{Eqn. 26}$$

$$E_{system} = \frac{Power\ Produced + Steam\ Heat\ Demand}{Fired\ Fuel + Imported\ Steam + Imported\ Power}\ X\ 100 \qquad \text{Eqn. 27}$$

Where:

Site Power Demand	:	Total electrical energy produced (MJ/h)
Site Heat Demand	:	Total steam energy to users (MJ/h)
Fired Fuel	:	Total fuel fired (MJ/h)
Imported Steam	:	Energy imported into cogeneration system (MJ/h)
E_{system}	:	Overall thermal efficiency of cogeneration (%)
m_{steam}	:	Mass flow rate of steam to users (t/h)
m_{cond}	:	Mass flow rate of condensate returned from steam users (t/h)
H_{BFW}	:	BFW enthalpy (kJ/kg)
H_{steam}	:	Steam enthalpy (kJ/kg)
H_{cond}	:	Condensate return enthalpy (kJ/kg)
m	:	Mass flowrate (t/h)
$HRSG_{fuel}$	:	Mass flowrate of fuel sent to HRSG (t/h)
$Boiler_{fuel}$	:	Mass flowrate of fuel to boilers (t/h)
LHV	:	Lower heating value of fuel (kJ/kg)
m_{import}	:	Mass flowrate of steam import (t/h)
H_{import}	:	Enthalpy of steam import (kJ/kg)
$Power_{GTG}$	:	Power output of GTG (MW)
$Power_{STG}$	:	Power output of STG (MW)
$Power_{IMP}$	:	Power import (MW)
E_{import}	:	Efficiency of steam generation for steam import, assume 92% if not known (%)
E_{PIMP}	:	Efficiency of generation for imported power, assume 38% if not known (%)

The overall thermal efficiency will vary depending on the amount of steam that is sent to the end users as heating steam, as shown by the example in Figure 11.

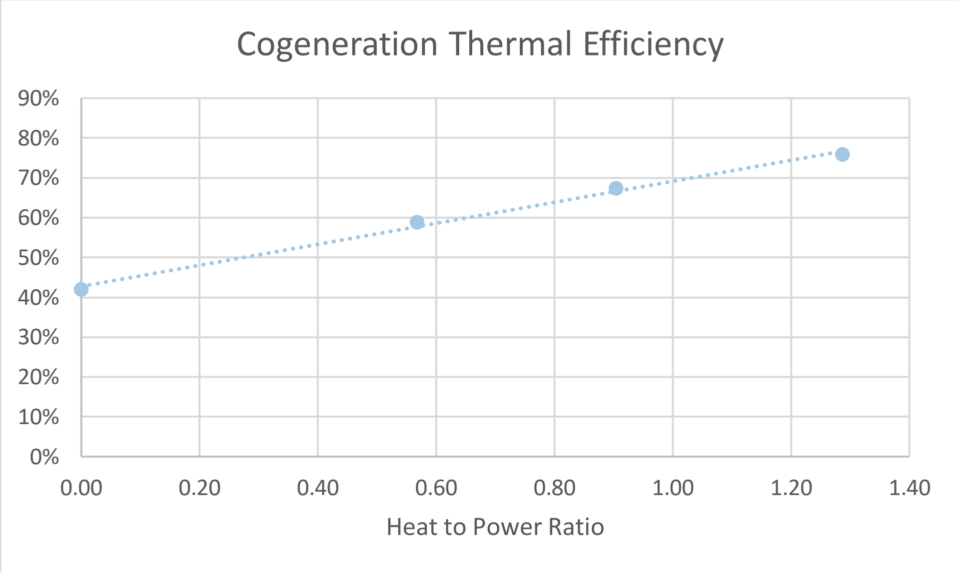


Figure 11: Example of variation in thermal efficiency with heat to power ratio

Figure 11 shows that as more heat is sent to the end users, the efficiency of the cogeneration system increases. This is because less steam is sent through the condensing section of the STG to generate the required power for the site, resulting in less heat loss from the turbine to the cooling system (condensing exchanger on the STG pulling the vacuum).

To reduce steam and power load will require an assessment of the end users to see if there is scope to reduce steam use by improving heat recovery and by making process changes, and improvements to reduce electric power consumption.

2. Energy performance gap

The energy gap between an existing system and a best practice system should ideally be determined by rigorous calculation of the system by applying best practice equipment efficiencies and practices (for example maximising condensate recovery). However, an estimate of the target cogeneration efficiency can be made using the R-curve, which is the relationship between power to heat (as steam) ratio (R) for a system and the cogeneration efficiency.

Figure 12 shows a typical R-curve for different cogeneration systems, showing that the most efficient system will consist of back-pressure steam turbines and a GT & HRSG. This configuration will, therefore, be used to benchmark the cogeneration efficiency for a site according to their power and steam heating demands. The procedure for deriving the target cogeneration efficiency from the R-curve is given in Appendix C.

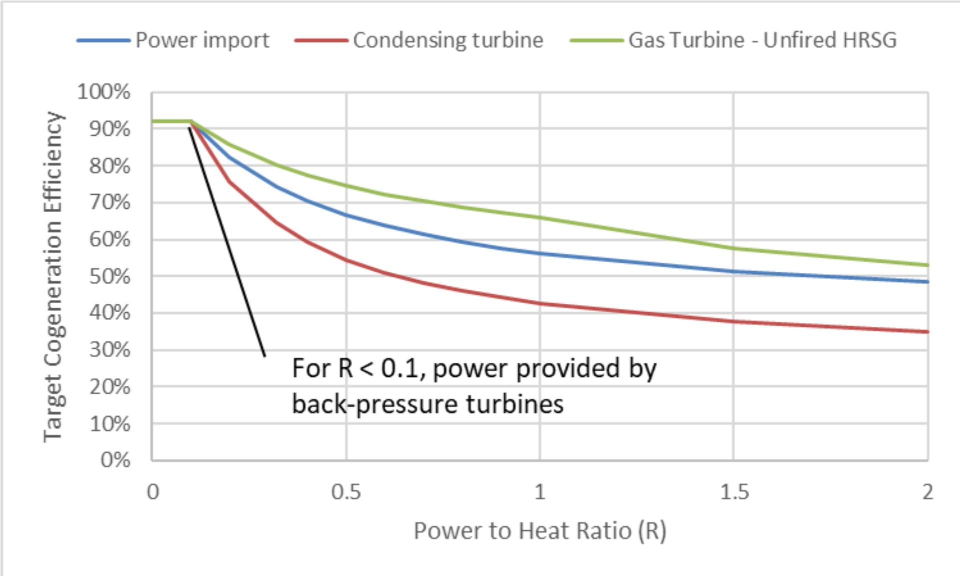


Figure 12: Example of R-curves for different configurations

3. GTG thermal efficiency

The GTG efficiency is mainly affected by:

- Design and the type of gas turbine
- Loading. Maximum efficiency is normally achieved when the GTG is operated at maximum power output, but the efficiency can drop significantly if the machine is operated below maximum power.
- Inlet (ambient) air temperature. Higher air temperatures necessitate higher compressor power and thus reduces the power output.
- Machine problems. If there is fouling or mechanical problems in the machine the power output maybe reduced compared to the design output.

The efficiency of the GTG can be determined from plant measurement of the power output and fuel flow to the GTG, such as:

$$GTG\ Efficiency\ (\%) = \frac{Power_{GTG}\ X\ 3600}{m_{GT\ fuel}\ X\ LHV_{fuel} + m_{ws}\ X\ H_{ws}}\ X\ 100 \qquad \text{Eqn. 28}$$

Where:

$m_{GT\ fuel}$	:	Mass flow rate of fuel (t/h)
LHV_{fuel}	:	Lower heating value of fuel (kJ/kg)
m_{ws}	:	Mass flow rate of water/steam injection into GTG (t/h)
H_{ws}	:	Enthalpy of water/steam injection into GTG (kJ/kg)
$Power_{GTG}$	:	Power output of GTG (MW)

To assess the performance of the GTG, the efficiency calculated in Eqn. 28 should be compared to the design efficiency at the operating power output. Typical gas turbine efficiencies range from 28% to 42%[7].

4. HRSG thermal efficiency

Elements to consider maximizing HRSG efficiency:

- The stack losses have to be minimised by reducing stack temperature (by increasing heat recovery on the convection section – e.g. installing an economiser)
- Steam production (by increasing heat recovery on the convection section – e.g. installing an economiser) and steam enthalpy (by generating steam at highest possible pressure – as long as it is aligned with site steam system level) should be maximised

The efficiency of the HRSG, can be determined by rigorous heat balance if the following information is available:

- The GTG exhaust flow, temperature and composition
- HRSG fuel flow and composition
- HRSG stack temperature

The above data is not always available so the HRSG efficiency can be calculated as follows:

$$HRSG\ Efficiency = \frac{m_{steam}\ X\ H_{steam} - m_{BFW}\ X\ H_{BFW}}{m_{HRSG\ fuel}\ X\ LHV_{HRSG\ fuel} + Heat\ from\ GTG}\ X\ 100 \qquad \text{Eqn. 29}$$

The heat content of the GTG exhaust can be calculated as:

$$Heat\ from\ GTG = m_{ex}\ X\ H_{ex} \qquad \text{Eqn. 30}$$

In cases where the GTG exhaust flow and composition are not known, the heat content of the exhaust can be approximated as:

$$Heat\ from\ GTG = Power_{GTG}\ X\ \left(\frac{1}{GTG\ Efficiency} - 1\right) * 3600 \qquad \text{Eqn. 31}$$

Where:

m_{BFW}	:	Mass flow rate of BFW (t/h)
m_{steam}	:	Mass flow rate of steam (t/h)
$m_{HRSG\ fuel}$	:	Mass flow rate of HRSG supplementary fuel (t/h)

LHV_{fuel}	:	Lower heating value of HRSG supplementary fuel (kJ/kg)
H_{Steam}	:	Steam enthalpy (kJ/kg)
H_{BFW}	:	BFW enthalpy (kJ/kg)
m_{ex}	:	Mass flow of gas turbine exhaust (t/h)
H_{ex}	:	Enthalpy of gas turbine exhaust (kJ/kg)
$Power_{GTG}$	:	Power output of GTG (MW)
Heat from GTG	:	Available heat from gas turbine exhaust (MJ/h)

As with a conventional boiler, the blowdown from the HRSG will affect steam production (refer to Assessment Framework Boilers). The HRSG blowdown rate should, therefore, be checked.

- HRSG blowdown rate (this value depends on the quality of the boiling feed water – BFW – best practice expected at 1%[6])

The HRSG blowdown rate can be calculated from the difference between HRSG BFW flowrate and steam production.

For a fired HRSG, the efficiency will vary according to the amount of fuel used which will vary according to steam production. For an unfired HRSG, the efficiency will depend on its design.

5. HRSG stack temperature

Hot exhaust gas from the gas turbine is a source of high temperature heat that can be recovered. Heat from the exhaust gas is recovered into BFW and steam to generated high pressure superheated steam in the HRSG.

The stack temperature is the measured temperature of the exhaust gas that exits into the atmosphere after the HRSG. This temperature measurement should be taken after the economizer or any stack heat recovery exchanger to ensure that existing heat recovery measures have been accounted for.

Best practice stack temperature is at about 150°C[6] assuming natural gas or clean fuel gas is burnt.

The acid dew point of the stack temperature is directly correlated with the sulphur content of the fuel. Stack temperature has to be kept higher than the acid dew point temperature to avoid acid condensation.

6. STG efficiency

The efficiency of a STG is governed by:

- Isentropic efficiency of the machine
- Pressure of exhaust. A lower pressure will increase power output.

Using an example of a 2-stage STG with extraction and condensing section, the isentropic stage efficiencies of the extraction and condensing stages can be computed as follow.

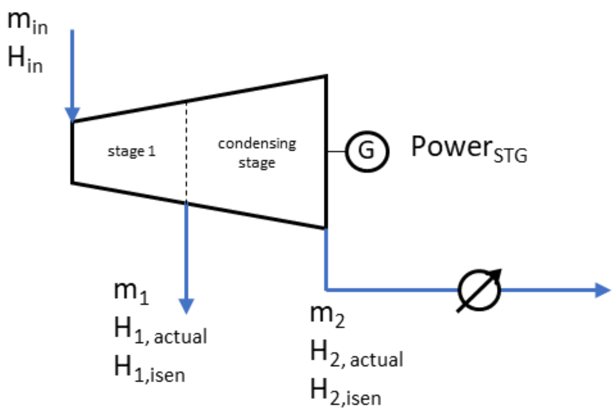


Figure 13: Example of a 2-stage steam turbogenerator

The isentropic efficiency of the extraction stage of the STG can be determined from the extraction steam pressure and temperature, and inlet steam pressure and temperature as illustrated below.

$$E_{stage\_1} = \frac{H_{in} - H_{1,actual}}{H_{in} - H_{1,isen}} \, X \, 100 \qquad \text{Eqn. 32}$$

$$Power_{stage\_1} = \frac{m_1 (H_{in} - H_{1,actual})}{3600} \qquad \text{Eqn. 33}$$

It can be difficult to calculate the isentropic efficiency of the condensing stage, as the quality of the steam (amount of water that has condensed in the exhaust) is not measured and difficult to determine. There are two possible approaches that can be used:

1. Calculate enthalpy of steam from pressure and quality either using design wetness of the steam to the condenser or by assuming that exhaust is 5% liquid (typical maximum allowable) if no design data is available.
2. Determine energy balance across turbine from the total power output. Power output of condensing section can be calculated by subtracting power output of extraction section. Conditions of the condensing extraction can be calculated as:

$$Power_{condensing\ stage} = Power_{STG} - Power_{stage\_1} \qquad \text{Eqn. 34}$$

$$E_{condensing\ stage} = \frac{Power_{condensing\ stage} \, X \, 3600}{m_2 \, X \, (H_{1,actual} - H_{2,isen})} \, X \, 100 \qquad \text{Eqn. 35}$$

Where:

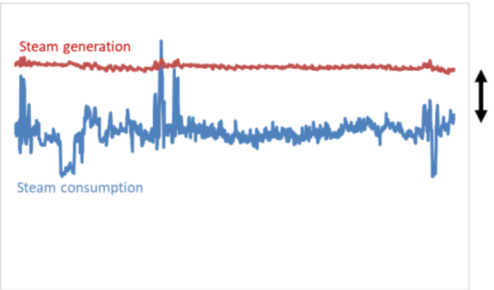
E_{stage}	:	Isentropic stage efficiency (%)
m_{in}, m_1, m_2	:	Steam mass flow rate of turbine inlet, extraction and condensing sections
H_{in}, H_1, H_2	:	Actual steam enthalpy at inlet, extraction and condensing conditions (kJ/kg)
$H_{1,isen}$, $H_{2,isen}$	:	Isentropic steam enthalpy at inlet, extraction and condensing conditions (kJ/kg)
$Power_{STG}$	:	Total power generated from the STG (MW)
$Power_{stage\_1}$	:	Power generated from the stage 1 only (MW)
$Power_{condensing\ stage}$	:	Power generated from the condensing stage only (MW)

To assess the performance of the STG, the calculated isentropic efficiencies should be compared to the design value, as the efficiency is machine specific.

7. Overall mass and energy balance of steam system

The generation and consumption of steam at the plant should be accounted for to quantify the gaps in steam balance. This accounting will require a comprehensive set of permanent instrumentation. Long-term tracking of the gap between total steam generation and consumption may yield insights to the performances of the heating system.

An example of a steam generation and consumption chart is shown below.



This gap between generation & consumption of steam may be attributed to

- Plant upsets, operating modes, product slates
- Deterioration in heat exchangers, insulation
- Site steam losses and leaks (malfunctioning steam traps)
- Instrumentation errors
- Assumptions due to lack of instrumentation
- Weather

Figure 14: Example steam system heat balance

For a complex cogeneration system, heat balance can also be performed at the steam header level, accounting for steam flows in and out of each header.

Heat losses through pipe insulation, steam leakages and failed steam trap do contribute to the gap between steam generation and consumption curve. However, these losses are difficult to quantify, especially when industrial steam systems tend to be expansive.

Steam pipe insulation and steam traps should be routinely reviewed for deterioration or failures. Advanced monitoring tools can also be deployed for the condition monitoring of steam traps for timely intervention.

8. Condensate recovery

Heat is also lost through the discharge of hot condensate that usually comes from heating steam use. The recovery of hot condensate should be maximised whenever possible so that lesser deaeration steam is needed to heat condensate to its saturation temperature. This also helps in reducing the demand for make-up water into the cogeneration system.

Condensate recovery can be calculated by performing a mass balance around the deaerator.

$$\%\ condensate\ recovery = \frac{m_{condensate\ return}}{m_{BFW\ from\ deaerator}}\ X\ 100 \qquad \text{Eqn. 36}$$

Where:

$m_{condensate\ return}$	:	Mass flow rate of return condensate to deaerator (t/h)
$m_{BFW\ from\ deaerator}$	:	Mass flow rate of BFW from deaerator (t/h)

Eqn. 36 should be modified accordingly depending on the availability and positioning of condensate flowmeters. Flow rate of make-up water to deaerator, if available, can also be used for computation of % condensate recovery.

9. BFW pump specific energy consumption

In some heating systems, the energy consumption of the BFW pump may be significant. The specific energy consumption (SEC) of the pump can be monitored to ensure that potential for energy saving can be easily identified.

Changes to the pump SEC may occur if there are significant and prolonged changes to the plant operations, design or loading. Hence, pump SEC should be monitored over the long term for significant changes. This can provide indications that energy saving projects on the pump application may become viable if SEC increases significantly permanently or for prolonged periods of time.

There is no standard benchmark for pump SEC as it is heavily dependent on its application, pump design, system pressure, fluid properties etc.

10. Deaerator pressure

Deaerators typically use low pressure steam to provide heating and stripping of dissolved gases from boiler feed water. As deaerators can operate across a range of pressures, it uses varying amounts of steam.

The operating conditions of a deaerator is not a simple case of maximising or minimizing the pressure. The optimization of deaerator pressure becomes more complex in a cogeneration system as it is heavily dependent on the utility system and steam balance.

In cases where there is an excess of low pressure steam, sites may want to consider increasing deaerator pressure to consume more steam to produce hotter boiler feed water. Consequently, this may lead to a negative energy impact on the heat recovery at boiler and furnace stacks economizers as the temperature approach becomes smaller.

On the other hand, sites that are letting down medium pressure steam to low pressure in order to fulfil the deaeration steam demand may consider reducing the deaerator pressure. This reduces low pressure steam demand and in turn, reduce the letdown steam flow.

The modelling of the steam system is typically required to assess the impacts of changing deaerator pressure on the steam balance and other associated energy recovery.

6.3 Monitoring of Improvements

Monitoring of the improvements in the system should be done by:

- Tracking the overall system (cycle) efficiency
- Tracking specific equipment (GTG, HRSG, STG) efficiency, for instance:
    - GTG: optimisation of the GTG load (working near design load)
    - HRSG: A reduction in stack temperature
    - STG: a reduction of the amount of condensing power

6.4 Data Requirements

The following information is required to carry out a comprehensive analysis of the performance of a cogeneration system.

Plant Measurements:

- Fuel analysis (type, flow rate, temperature, lower heating value) to GTG and HRSG
- Water/steam injection into GTG (flow rate, pressure, temperature)
- Combustion air temperature
- HRSG stack temperature
- HRSG steam flow and conditions (pressure, temperature)
- HRSG boiler feed water flow and conditions (pressure, temperature)
- STG inlet, extraction and condensing conditions (pressure, temperature, flow)

- Condensate, BFW and make-up water conditions (temperature, flow)
- GTG / STG power output
- Steam import from outside sources (pressure, temperature, flow)

Datasheets:

- GTG, HRSG and STG specification document (design data)
- GTG, HRSG and STG inspection report
- Boiler datasheet
- BFW pump datasheet

7 References

[1] https://www.singstat.gov.sg/find-data/search-by-theme/economy/national-accounts/visualising-data/gross-domestic-product-dashboard

[2] https://www.ema.gov.sg/Singapore-Energy-Statistics-2019/Ch03/index3

[3] NEA tender briefing on The Provision of Consultancy Services to Study Energy Performance of Heating Systems in Oil Refining, Petchem and Chemical Plants

[4] KBR standards and specifications for furnace/fired heaters design/performance

[5] KBR standards and specifications for ethane cracker furnace design/performance

[6] KBR standards and specifications for boiler design / performance

[7] Gas Turbine World Handbook 2014

Appendix A – Assessment Methodology of Downstream Energy Use

In the assessment frameworks for heating systems, the reduction of heating loads can be achieved through the optimization of energy use at the downstream users. In the refinery, petrochemical and chemical industry, downstream users of energy commodities are typically in heat exchangers, distillation column reboilers, reactor steam jackets etc.

The following approaches can be broadly used to optimise downstream energy use.

- Pinch analysis – for the optimization of complex heat exchanger networks
- Process optimization – for distillation and other plant specific processes

Pinch Analysis

The optimization of energy use in a complex network of heat sources, heat sinks and heat exchangers, is best achieved through the application of heat integration (via energy pinch analysis techniques). Pinch analysis is a systematic technique, based on thermodynamic principles, for the matching the heat sources to the heat sinks to achieve maximum energy recovery (minimum utility consumption). This methodology can be used in green field projects as well as for retrofitting and debottlenecking of existing plants.

The application of pinch analysis typically involves the following key steps

1. Identify hot and cold streams available in a plant
    - Hot streams refer to material streams that needs to be heated up. Cold streams refer to material streams that needs to be cooled down.
    - Duties, supply and target temperatures of hot and cold streams need to be extracted. These parameters are typically available as measured data.

2. Specify an appropriate minimum approach temperature (ΔT_{min}) for the specific industry
    - For green field projects, the selection of ΔT_{min} is an economic decision that balances between capital and energy costs. A lower ΔT_{min} would mean lower utility requirements, but at the expense of additional heat transfer area, leading to a higher capital cost.
    - For brown field projects, the selection of ΔT_{min} follows a figure that is typical of the industry that the plant is in. Based on KBR experience, the following ΔT_{min} figures are applied to allow project payback within 5 years.
        - Refining processes : 20 – 40 °C
        - Ethylene Cracker processes (hot end) : 10 – 25 °C
        - Chemical processes : 10 – 20 °C

3. Generation of pinch targets (hot and cold energy targets)

   - Through the use heat integration, hot and cold composite curves can be generated as shown in Figure 15 below. From this curve, the minimum hot ($Q_{H,min}$) and cold ($Q_{C,min}$) utility targets are quantified.

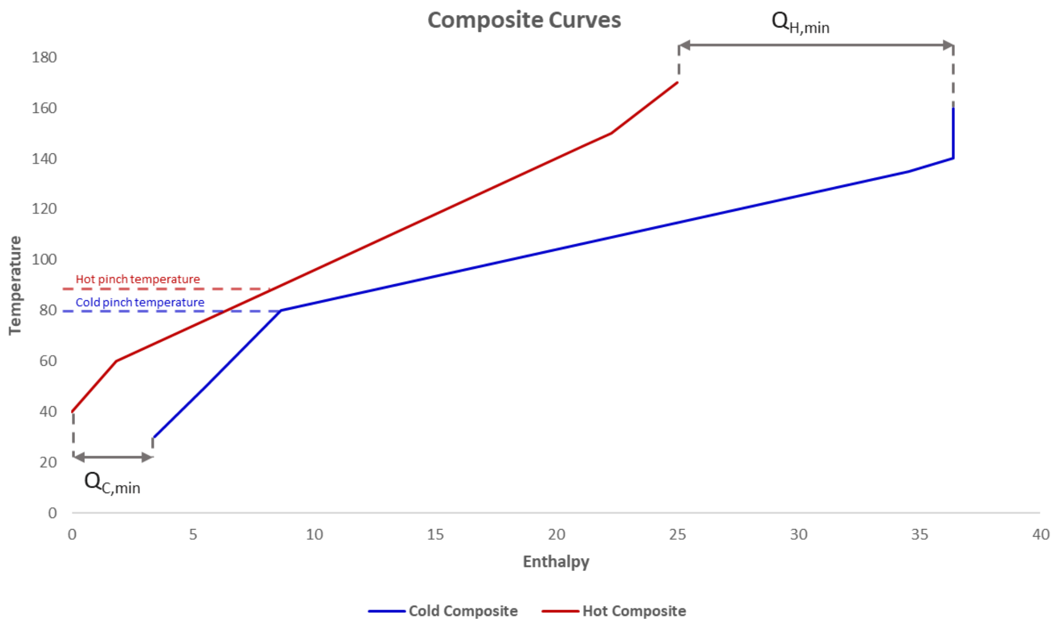


Figure 15: Example of hot and cold composite curves

4. Benchmark actual site energy use against energy targets

   - Hot Pinch Gap = $Q_{H,actual} - Q_{H,min}$
   - Cold Pinch Gap = $Q_{C,actual} - Q_{C,min}$

   Where $Q_{H,actual}$ and $Q_{C,actual}$ are actual duties of hot and cold utilities used.

5. Study of heat exchanger network and generation of retrofit project ideas

   - The above analysis will also indicate the hot and cold pinch temperatures that are specific to each plant, depending on the heating and cooling profile of the material streams. The energy performance assessment of heat exchanger networks will involve the elimination of cross-pinch heat transfer and utility swaps (maximizing the use of available cheap utility).
   - For complex pre-heat trains, projects need to be simulated in a process simulation model. This is to understand the dynamic impacts of increasing heat recovery at one heat exchanger on the entire system.

As the above approach covers all material streams that requires heating and cooling, all available waste heat sources will be evident. Opportunities to maximise steam generation from waste heat sources will be assessed in conjunction with the site utility system. Applications of low-grade heat recovery techniques can also be evaluated as appropriate.

Process Optimization

The operations of plant processes can be reviewed for energy saving opportunities without impacting product outputs. Common equipment such as distillation columns can be reviewed for opportunities to maximise waste heat recovery or reduce utility consumption (as covered in pinch analysis). There may be additional opportunities such as

- Review of column feed temperature and location
- Review of column reflux ratio and product specifications (actual vs required)
- Selection of appropriate hot and cold utility
- Review of column operating pressure
- Opportunities for side or parallel reboilers and condensers

The above list is not exhaustive.

Appendix B – Addressing Data Gaps

The energy performance assessment of heating systems will involve the use of existing plant instrumentation as a basis for data collection. Most industrial heating systems come with instrumentation systems that are connected to the plant Distributed Control Systems and data historians.

Utility flows, such as fuel, steam or hot oil, to each downstream user should be monitored via flow and temperature meters. In practice, not all users will come with its own comprehensive set of instruments needed to compute its utility consumption. Alternative approaches can then be deployed to estimate its utility consumption. These approaches are detailed below, ranked in order of preference.

1. Calculate the duty of heat exchanger using process stream parameters (flow rate, temperature inlet/outlet and specific heat capacity).The utility consumption at this heat exchanger can then be estimated. Process simulators and/or steam and water thermodynamics will be relied upon for these calculations. This method assumes that heat gained from the process stream equals to the heat lost by the utility stream in the heat exchanger.
2. Use of process or heat exchanger design data sheets to estimate its utility consumption
3. Deployment of portable instrumentation tools (only for critical parameters)

Electrical consumption of typical rotating equipment such as pumps and compressors can be estimated from its design curves. Operating data such as the flow rate and differential pressure can be plotted on the design performance curve to attain its estimated electrical consumption. If design curves are not available, then theoretical calculations can be performed based on design efficiency.

If stack temperature measurements are not available, then design stack temperature can be used. This will be valid if the boiler / furnace has not undergone revamps that may affect its stack heat since its construction. The deployment of portable instrument tools should be used only as a last resort for measurement of critical parameters. As this methodology involves significant site work, appropriate risk assessment in line with company procedures must be conducted. Safety concerns such as work-at-height and getting into close proximity with hot fluids must be considered. Measurement parameters are deemed as critical if

- The heating system efficiency cannot be quantified without this information.
- The utility user is a significant energy consumer.

For critical parameters without existing instrumentation, the plant should strongly consider installing permanent instruments as a long-term solution. This will allow the plant to minimise safety risks and financial costs of deploying portable instruments. The measurement accuracy of portable instruments can be questionable and heavily dependent on the way its deployed.

The following table contains information on short term data logging approaches that may be deployed for data collection of critical variables in heating systems.

Table 5: Possible short-term data logging approaches for critical parameters of heating systems

S/N	Measurement Approach	Measured Parameter	Typical Instrument Accuracy
1	Laboratory analysis	Fuel lower heating value	-
2	Ultrasonic flow meter	Gaseous fuel flow (e.g., natural gas, fuel gas) Process stream (gaseous) flow	+/- 2.0%
		BFW flow rate Process stream (liquid) flow rate	+/- 2.0%
3	Platinum Resistance Thermometers	BFW temperature Stack temperature	Variable
4	Handheld infrared camera	Stack temperature	+/- 2.0%
5	Flue gas analyser	Stack O_2 / CO / NOx concentrations	+/- 0.3%
6	3-phase energy logger	Electrical power measurements	+/- 0.7%
9	Humidity and temperature meter	Ambient temperature Relative humidity	+/- 1.0 C

Appendix C – Using the R-curve to determine target cogeneration efficiency

For a steam system, the power to heat ratio (R) determines the maximum cogeneration efficiency that can be achieved.

- If R is less than 0.1 (exact number dependent on steam header pressures and steam demand at each header, range 0.05 to 0.15), then power for the site can be supplied by back pressure turbines which generate the required power, with steam to the turbines provided by boilers. A back pressure turbine generates power at the efficiency of the boilers, as all the steam from the exhaust of the turbine is used for heating purposes. For a best practice system, the boiler efficiency is 92%.
- For higher site power demands (R>0.15), it is not possible to use back pressure turbines to generate power as the steam demand is not high enough. In this situation, the site can either import power or can generate power with condensing turbines or with gas turbines, provided the heat from the gas turbine is recovered in a HRSG. The more efficient option is to use a GT & HRSG.

The figure below shows how the power to heat ratio (R) affects the cogeneration efficiency for different power generating cycles.

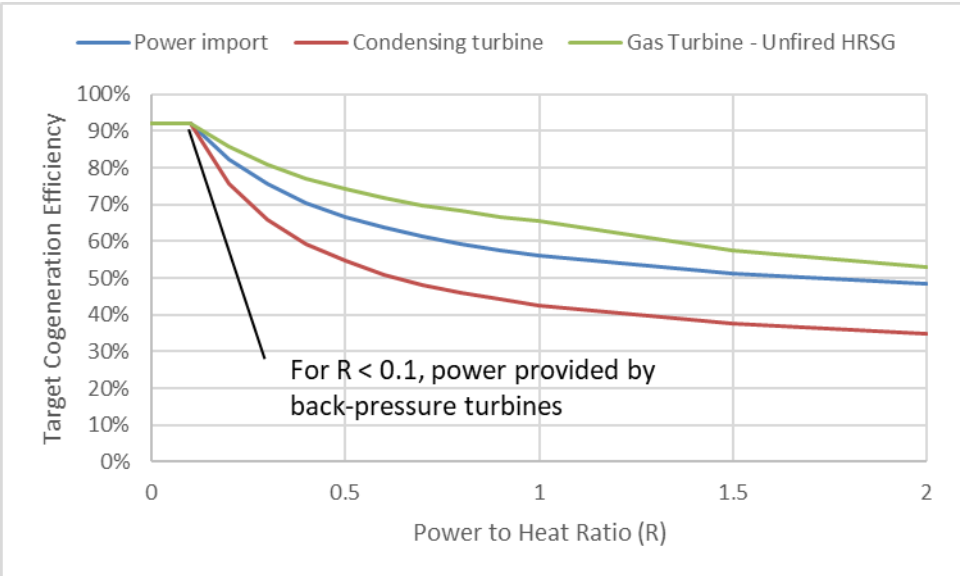


Figure 16: Cogeneration efficiency for various power generating cycles

For the GTG cycle, the target cogeneration efficiency can be calculated using the following equations.

$$R = \frac{Site\ power\ demand}{Site\ heat\ demand} \qquad \text{Eqn. 37}$$

$$R_{BPT} = \frac{Backpressure\ power}{Site\ heat\ demand} \quad \text{Eqn. 38}$$

$$E_{targ} = \frac{1+R}{\left\{\frac{(R-R_{BPT})}{E_{GTG}} + \frac{\left[1+R_{BPT}-\left(1/E_{GTG}-1\right)(R-R_{BPT})E_{HRSG}\right]}{E_{boiler}}\right\}} \quad \text{Eqn. 39}$$

Where:

E_{targ}	:	Target cogeneration efficiency
R	:	Site power to heat ratio
R_{BPT}	:	Site power from back pressure turbines to heat ratio, assume 0.1 if not possible to calculate
E_{GTG}	:	Gas turbine efficiency, assume 30%
E_{HRSG}	:	Unfired efficiency of the HRSG, assume 50%
E_{boiler}	:	Boiler efficiency, assume 92%

The table below show the relationship between R and the target cogeneration efficiency for the GT & HRSG cycle. This data is based on the following assumptions:

- Boiler efficiency at 92%
- GTG efficiency at 30%
- HRSG efficiency at 50% (no fuel firing)

Table 6: Effect of R on Target Cogeneration Efficiency for a GT & HRSG Cycle

R	Target Efficiency
0.0	92%
0.1	92%
0.2	86%
0.3	81%
0.4	77%
0.5	74%
0.6	72%
0.7	70%
0.8	68%
0.9	67%
1.0	65%
1.5	58%
2.0	53%

To determine the target cogeneration efficiency the following steps are required:

- Calculate site power demand (Eqn. 22)
- Calculate site heat demand (Eqn. 23)
- Calculate site R (Eqn. 37)
- Calculate power from back pressure turbines and calculate R_{BPT} (Eqn. 38)
- Calculate target efficiency (Eqn. 39)

The following example illustrates these steps, based on the following data.

- Site power demand of 10 MW
- Site steam demand of 30 MW
- Site R = 10 / 30 = 0.333
- Back pressure power is 3 MW, so R_{BPT} = 3 / 30 = 0.1

From Eqn. 39 above, at R of 0.333, the target cogeneration efficiency is 79.5%, which is calculated as follows:

Target = (1 + 0.333) / ((0.333 – 0.1) / 30% + (1 + 0.1 – (1/30% -1) *(0.333 – 0.1)*50%)/92%) = 79.5%