Energy & Petroleum Regulatory Authority

VOLUME TWO

Hot Water and Steam Systems Energy Auditing Guidebook

1. Introduction

Hot water and Steam systems are part of the thermo-fluid systems as was categorised in Volume One of this guidebook. The application of these systems ranges from domestic and commercial to industrial uses. For example, in the domestic set up, hot water is used for bathing, cooking and cleaning. In commercial and industrial facilities, steam and hot water systems are used for process heating, sterilization, laundry, space heating and drying. These systems can be powered by different sources of energy and equipment.

In energy consuming facilities, hot water and steam can be generated from:

i. Solar water heating
ii. Open fire heating
iii. Electric heating (domestic heating elements)
iv. Heat pumps
v. Fossil fuel and biomass fired Boilers, and Electric boilers

Whereas understanding the working principles and efficiency of all these systems is important, this guidebook shall focus on the boiler powered hot water and steam systems. These are the most prevalent systems in the commercial and industrial facilities. This volume provides steps in auditing hot water and steam systems. To effectively audit this system, it is imperative for the energy auditors to understand the components of the system.

2. Components of hot water and steam systems energy audit

Figure 1 illustrates the components of hot water and steam systems

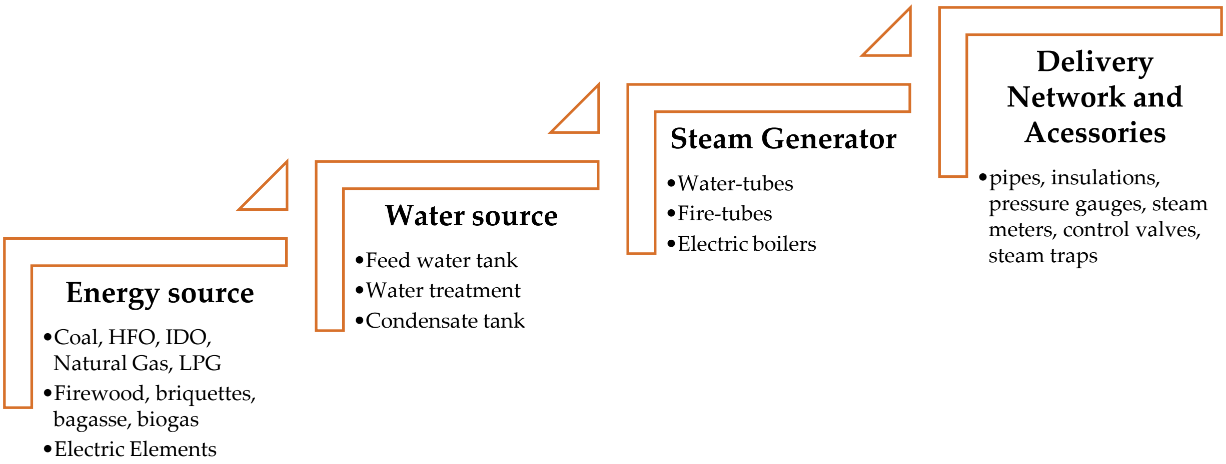


Figure 1: Hot water and Steam System parts

Figure 1 guides the energy auditor on the parts of the hot water and steam systems they require to understand before they begin the energy auditing processes.

Energy is the highest contributor to the operational costs of the steam system. It is used to increase the temperature of water, transforming it into hot water and steam. Heat for firing boilers is obtained through combustion process where the fuel is oxidised by air induced into the burner. Electric boilers on the other hand, obtain heat by resistance heating or electrode heating.

Water used in the boilers is supplied through the feed water tank. The feed water tank is supplied from the water treatment plant and condensate tank. In some processes, condensate water may not be considered for addition into the feed water tank due to requirements of steam purity. The water from the feed tank is pressurized to the required pressure, using pressure pumps, before being fed to the boiler.

There are three main types of boilers: water-tubes, firetubes and electric boilers. The water-tubes and fire-tubes boilers are fired by fossil fuel or biomass. For water tubes boilers, water flows through the boiler tubes while the fire is confined in the shell. They are mainly used in electricity generating plants. The fire-tube boilers on the other hand convey fire through the tubes while water is confined in the outer shell. They come in relatively smaller sizes compared to the water-tubes boilers and commonly used in industrial hot water and steam systems. Electric boilers use electric elements through resistance heating or electrode heating to heat water and generate steam.

The generated steam is distributed to the point of use through a delivery network. The network consists of insulated pipes, control valves, pressure and temperature gauges, steam meters and steam traps.

3. Steps in hot water and steam systems energy audit

The overall performance of the steam system can be determined by direct or indirect methods. For the direct method, the auditor establishes the overall system efficiency by comparing energy in the useful steam produced to the energy content of the fuel used. This can be done using equation 1.

$$\eta = \frac{\dot{m}(h_s - h_w)}{\dot{m}_f \times c_s} \qquad (1)$$

Where

η	Overall system efficiency
$\dot{m}$	Average steam mass flow rate over the operation cycle
h_s	Average steam enthalpy over the operation cycle
h_w	Average water enthalpy over the operation cycle
$\dot{m}_f$	Average fuel mass flow rate over the operation cycle
c_s	Calorific value of fuel

When calculating the overall system efficiency using the direct method, it is not possible to associate energy losses with a specific parameter. To determine the energy losses attributed to specific system components or processes, the indirect method is employed. In this method, the overall system energy efficiency is calculated by subtracting the percentage heat loss – from specific system components or process - from 100%.

Steam system efficiency by the indirect method is calculated using equation 2.

$$efficiency = 100 - \sum_{1}^{n} L_i \qquad (2)$$

Where

L_i	heat loss associated with a given heat loss parameter
n	number of parameters considered as sources of heat loss

For example, some of the heat losses associated with fuel-fired boiler steam systems are:

i. Loss due to dry flue gas (sensible heat)
ii. Loss due to hydrogen in fuel (H_2)

iii. Loss due to moisture in fuel (H_2O)

iv. Loss due to moisture in air (H_2O)

v. Loss due to carbon monoxide (CO)

vi. Surface losses due to radiation, convection and conduction.

vii. Losses due to incomplete combustion

Figure 2 illustrates the indirect method of establishing steam system efficiency as has been described.

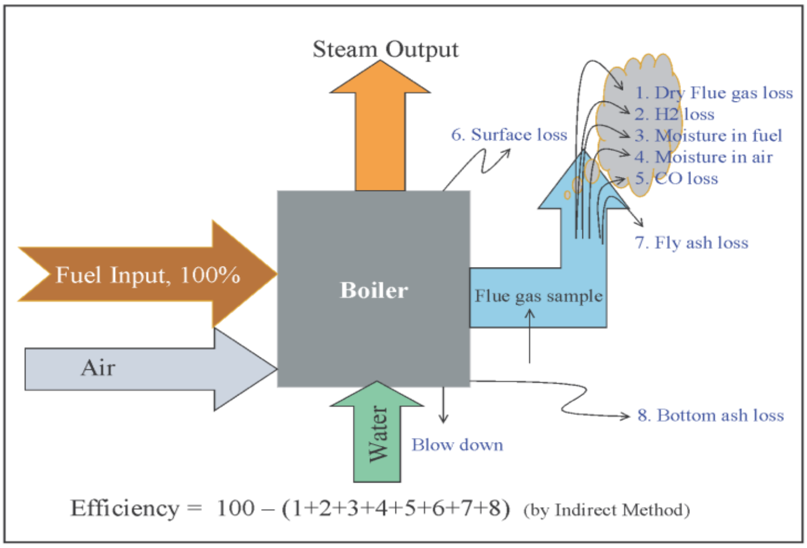


Figure 2: Indirect method of determining Steam system efficiency.

The energy audit of hot water and steam systems has three fundamental steps as illustrated in figure 3:

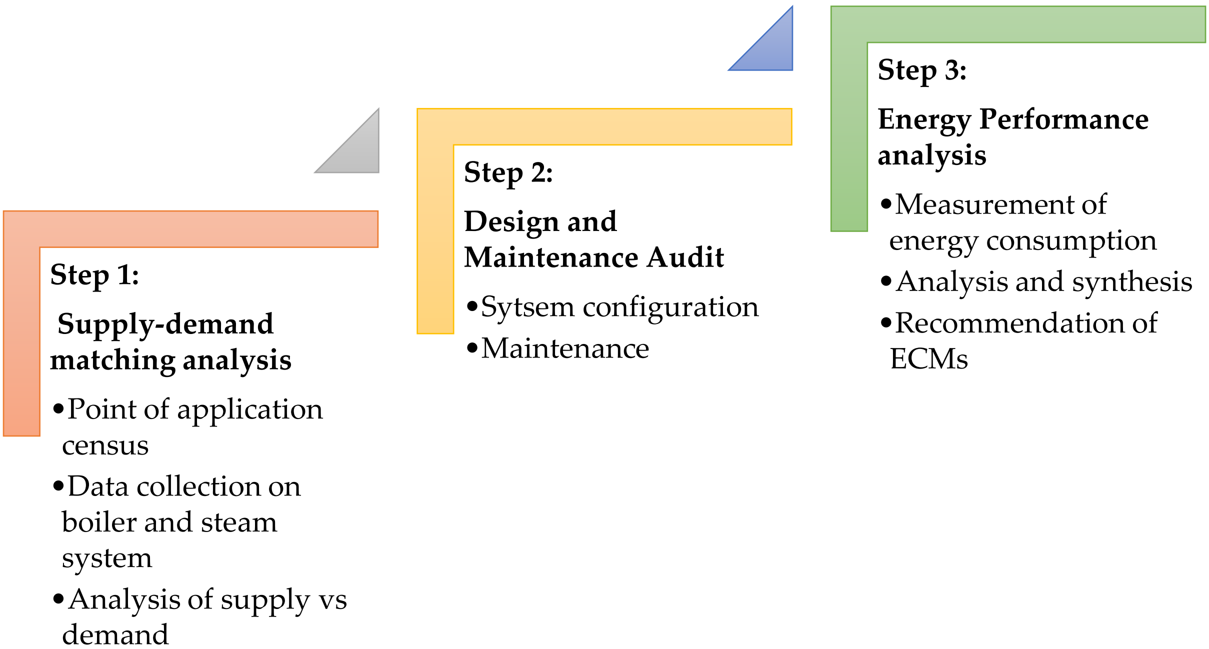


Figure 3: Steps of Auditing a Hot Water and Steam System

The processes illustrated in Figure 3 are sequential, with the results from the preceding step informing the analysis of the succeeding step.

3.1 Supply-demand matching analysis

For efficient operation of hot water and steam systems, the steam generated should as much as possible be wholly used at the application points. Situations where some of the hot water and steam generated is not used at the point of application result in inefficiencies. For example, 4000 kg/hr boiler supplying a 2000 kg/hr drying system leads to inefficient operation. During steam system audit, the auditor should determine the boiler size, working pressure and the end use requirements.
The boiler size and working pressure is obtained from the name plate as illustrated figure 3.

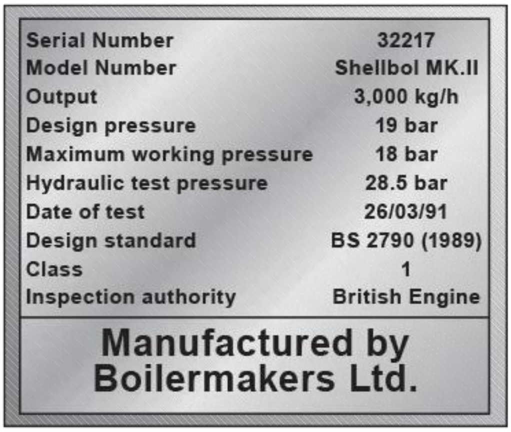


Figure 3: Boiler Name Plate

Figure 3 shows the name plate of a boiler with a capacity of 3,000 kg/h and maximum working pressure of 18 bars. This information should be used for comparison with demand requirements in the facility.
The auditor can determine the steam demand requirements in three ways:

i. The name plate of the end use equipment.
ii. User manual
iii. Measurement taken during operation.

The nameplate can be located at the radiator part of the equipment. Figure 4 illustrates a name plate of steam dryer (the end use application).

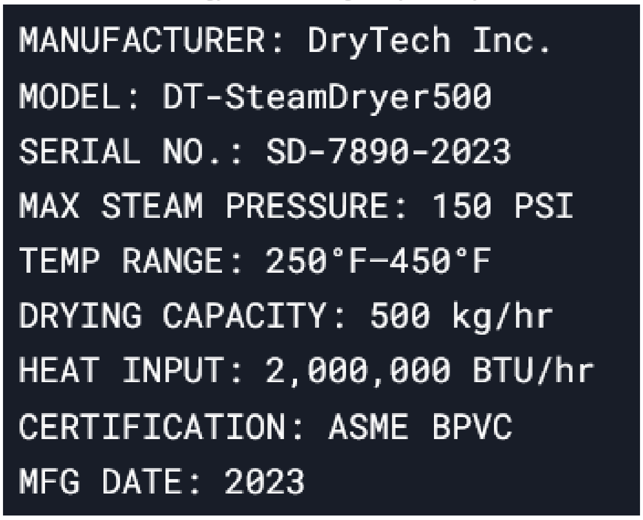


Figure 4: Steam dryer nameplate

Most steam using equipment on the shop floor will have nameplate such as the one shown in figure 4. The demand side census should encompass all of the equipment. The energy auditor should conduct matching analysis by converting both the boiler and the end use nameplate variables into power. The matching analysis can be presented in form of loading factor (Lf) and is computed as shown in equation 1.

$$Load\ Factor\ (\%) = \frac{Thermal\ power\ demand}{Thermal\ power\ supply} \times 100 \qquad 1$$

For efficient operation, the load factor for boilers should be between 75 % - 85%. It should be noted that overloading of the steam system may lead to compromised quality product or system shut down. In the event that the loading factor is within the recommended values, the auditor should still investigate areas of energy saving in the steam system. For both optimal and sub optimal loading situations, the auditor should go ahead to audit the design and maintenance of the system. However, major emphasis should be on the suboptimal operations.

3.2 Design and Maintenance Audit

In addition to loading conditions, energy performance of steam systems is also a function of size and conditions of the boiler and its auxiliary systems. The size is determined by the design of the system while the conditions are monitored and corrected through maintenance. An energy auditor should therefore be well versed with the design and operating principles of steam system.

The auditor should assess the design parameters of the boiler and its auxiliary system. Figure 5 (a slight modification of figure 1) can be used to guide the auditor on procedural steps of auditing the system design and maintenance.

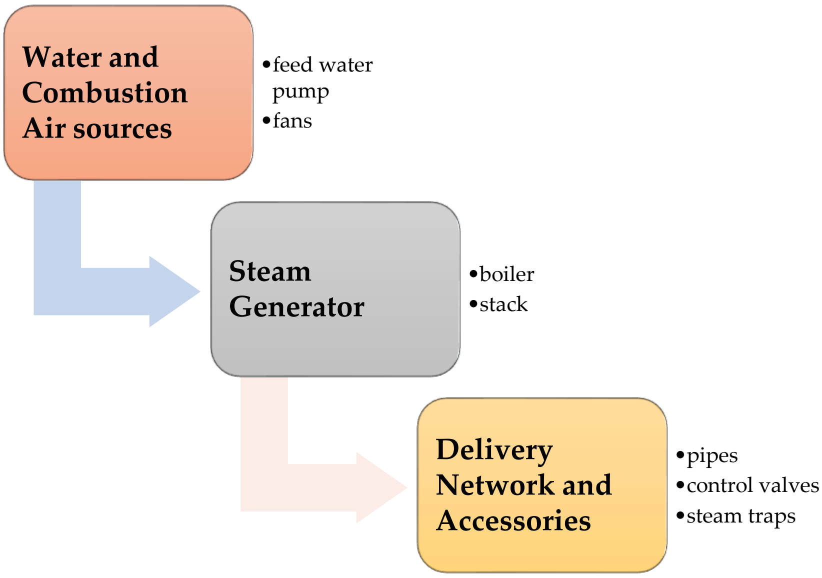


Figure 5: Steps of auditing the system design and maintenance

Feed water pumps and fans consume electric energy in the steam system. The following are the design and maintenance considerations for this equipment.

Feed water pump	From the pump specifications on the nameplate and pressure gauge, confirm if it is compatible with the pressure output of the boiler. For efficient operations, the maximum output pressure of the feed water pump should be 20% more than the maximum output pressure of the boiler. More information on savings computation for pumps is provided in the *Pump Auditing Volume* of this guidebook. Check mounting and coupling. If any of them is loose, they lead to vibrations hence loss of energy, poor performance and reduced equipment lifespan. The vibrations can be measured using a vibrometer, accelerometer, touching or hearing.

Fans	Confirm the fans' specification if it is compatible to the boiler combustion air requirements. The combustion air requirements can be obtained from the boiler's manual. For efficient operation, the maximum fans air flow requirements should be between 1.3 to 2 times more than the required boiler combustion air. The affinity laws can be used to compute energy savings due to fan design reconfiguration. This section has been dealt with comprehensively in the *Fans Auditing Volume* of this guidebook. Assess the stability of the fan by checking if there are vibrations. Such vibrations could be as a result of loose mounting, belts and coupling of the fans. Examine the air flow control method to check instances of excessive and permanent throttling.

Energy conservation measures relating to pumps and fans lead to saving of electric energy in the steam system.

For thermal energy audit, the auditor should assess the boiler and the stack. The following are the design and maintenance considerations to be considered.

Boiler	Assess the integrity of insulation. This can be done using visual inspection and thermal imaging cameras Confirm from their maintenance program if they have checked the structural integrity and clogging of the tubes. Clogging leads to poor heat transfer from combustion gases in the fire tubes to water. This can also be confirmed by measuring the temperature of the flue gas in the stack., Confirm the frequency of cleaning the tabulators in firetube boilers. It is recommended that they should be cleaned once a week to avoid clogging of the firetube.

Stack	Check the corrosion levels and clogging of the stack. Clogged stacks lead to poor combustion in the boiler tube due to slow rate of exhaust gas expulsion.

It should be noted that a poorly designed or maintained boiler and stack will not only lead to energy losses but also operational hazards and poor service delivery.

A whole system audit is essential for energy savings. This means that the analysis of energy performance should go beyond the boiler output. The steam delivery networks design and maintenance contribute to the overall energy performance of the steam system.

The following are the design and maintenance considerations to be considered when auditing the steam delivery network.

Pipes	Establish the integrity of the insulation. This can be done through visual inspections and use of thermal imaging camera. Check for the leaks. This can be done through audio and visual inspection. Examine the pipe network configuration geometry to establish unnecessary bends and joints.
Valves	Assess for the correct use of valves. There are some instances where gate valves are used for wrong purposes as pressure reducing valves. Carry out an inspection for leaks.
Steam traps	Establish the functionality of the steam traps. This can be done using thermal imaging cameras or infrared thermometers

A poorly designed and maintained delivery network leads to energy and steam losses, and hazardous environment.

The results obtained from steps 1 and 2 are useful inputs for energy performance analysis.

3.3 Energy Performance Analysis

Once the auditor conducts the supply-demand load matching, design and maintenance assessment, they should use the information obtained to guide the energy performance analysis. The data obtained during the preliminary stages can be used to propose energy conservation measures (ECMs). It can also be a pointer towards the need for more data collection. This section discusses the approaches of quantifying the energy performance and savings.

3.3.1 Steam Demand and Supply Matching

For energy performance analysis in this case, let us consider the boiler and dryer nameplates in figure 3 and 4 (Section 3.1). We start by converting the ratings into power (kW):

Boiler power capacity is calculated using equation 2

$$P_b = \frac{\dot{m} \times (h_s - h_w)}{3600} \qquad 2$$

Where

P_b	boiler capacity in kW
$\dot{m}$	mass flow rate kg/h (boiler capacity)
h_s	enthalpy of saturated steam in kJ/kg
h_w	enthalpy of feed water in kJ/kg

Mass flow rate $\dot{m}$ = 3000 kg/h
Maximum Working Pressure p = 18 bars
From steam tables:
enthalpy of dry saturated steam at 18 bars (h_s) = 2796.68 kJ/kg
enthalpy of feed water at 25°C and 1 bar (h_w)= 120.42 kJ/kg

$$P_b = \frac{3000 \times (2796.68 - 120.42)}{3600} = 2230.22\ kW$$

Using the Btu/hr specifications of the steam dryer, the power rating is 586 kW, converted into SI units. Assuming the boiler is serving 3 such dryers in the facility, the supply demand matching would be determined using equation 1:

$$Load\ Factor\ (\%) = \frac{586 \times 3}{2230.22} \times 100 = 78.8\%$$

In this example therefore, the loading can be said to be efficient, as was discussed in section 3.1.

Assuming the auditor found that there were only two such dryers, the loading factor would reduce to 52.6%. This therefore would require the auditor to make recommendations for improvements of the loading factor. Such recommendations must be justified through quantification of the potential energy savings. The savings must be in terms of primary energy used. In some cases, auditors present this savings in terms of Giga Joules. This practise may not necessarily be useful to the facility owner because they purchase energy in kWh (for electric boilers), Cubic Meters (for firewood boilers) and kgs (HFO boilers). It is essential to communicate to the facility owner in the language they best understand.

To quantify losses, the auditor should use the loading efficiency curve as presented in figure 6.

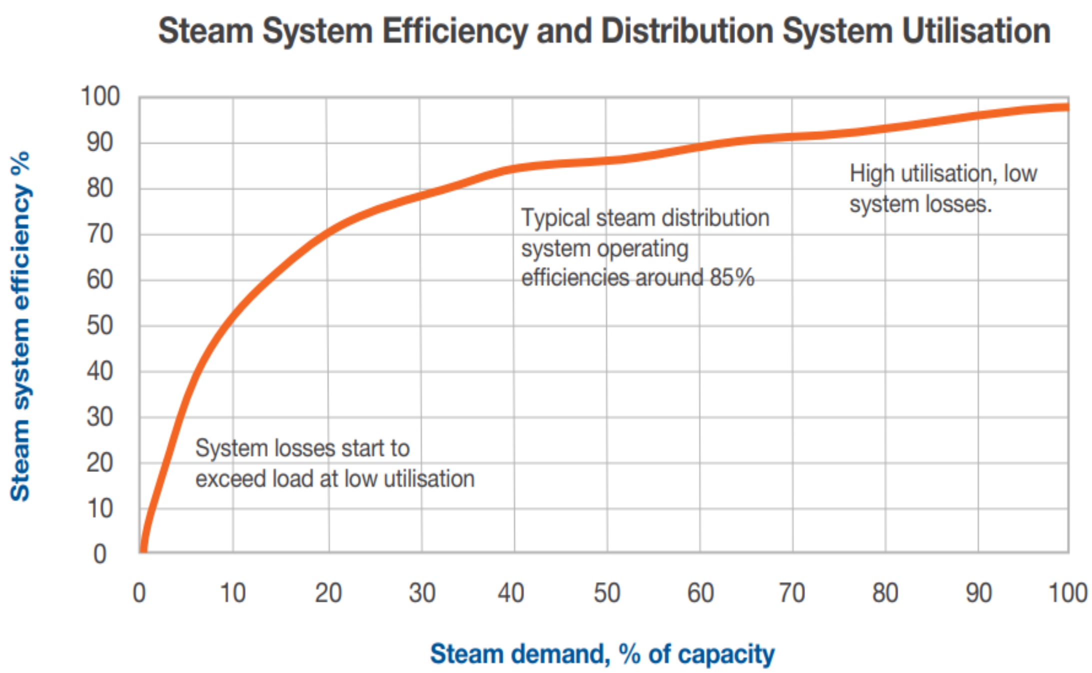


Figure 6: loading efficiency curve

From figure 6, at the loading factor of 52.6%, the efficiency is 85%.

Assume the auditor recommends that the loading factor to be improved to 80%, the efficiency of the boiler would improve to 94%. With this information, the primary energy saved can be computed as follows:

$$\text{Energy savings} = P_b\left(\frac{1}{\eta(\text{old})} - \frac{1}{\eta(\text{new})}\right) \times \text{t} \qquad 3$$

Where:

P_b	Boiler rating (kW)
t	Annual operation time of the boiler
$\eta(\text{old})$	Existing efficiency under current loading factor
$\eta(\text{new})$	Recommended efficiency under new loading factor

$$= 2230.22\left(\frac{1}{.85} - \frac{1}{0.94}\right) \times 7000$$

$$= 1{,}758{,}496 \text{ kWh}$$

In case of a firewood boiler, the kWh should be converted to kJ. The kJ units are then used with the wood's calorific value to compute the mass.

$$\text{Energy savings in kJ} = \ Energy\ kWh \times 3600\ kJ/\text{kWh}$$

$$= 6330586933.67 \text{ kJ}$$

To obtain the mass of firewood that would produce 6,330,586,933.67 kJ, the value is divided by the calorific value of the firewood, 17000 kJ/kg

$$Mass\ of\ wood\ (kgs) = \frac{6{,}330{,}586{,}933.67 \text{ kJ}}{17000 \text{ kJ/kg}} = 372{,}387 \text{ kgs}$$

The savings computed in this example can only be realised if the auditor recommends specific actions that would improve the loading factor, hence the efficiency. There is no one size-fits-all solution to loading factor improvement in steam systems. The auditor should analyse the operations and use the following as a guide to improve the factor:

i. In a case of a facility that uses two boilers to power two different processes (all the boilers underloaded), the auditor can recommend using one boiler to power the two systems. This would significantly raise the loading factor. However, such a recommendation should ensure that the single boiler can adequately power the two processes

ii. Sometimes poor loading factor could be caused by seasonal variations of production. For example, in a four-production line facility, two could be switched off during low season. In such a case, the auditor can recommend purchasing of an additional boiler to match the low production period. This recommendation can further be justified using life cycle cost analysis. This has been discussed in a different volume of this book.

iii. Steam requirements in a facility may also change, due to changes in processes. For example, in a tea factory, the change from batch withering to continuous withering reduces steam demand. The best practise in this case would be for the facility to design and install a smaller boiler to match the new requirement.

3.3.2 Design and Maintenance

Energy performance analysis on the design and maintenance of steam systems can result in substantial thermal and electrical energy savings. This analysis should encompass both the electrical (pumps and fans) and thermal systems (boiler and delivery network). This volume however focuses on the thermal systems. Fans and pumps have been handled in separate volumes of this guidebook. Readers are requested to visit the volumes for more details on the two systems.

For thermal systems, design and maintenance performance analysis should focus on the following:

i. Insulation
ii. Steam leaks

iii. Stack

Poorly insulated or worn out steam delivery networks lead to heat losses. An energy auditor should identify such issues and compute the attendant energy losses. To assess these losses the following information is necessary:

i. Steam pressure (bars)
ii. Surface temperature (^{0}C)
iii. Area of exposed surface (m^2)
iv. Overall heat transfer coefficient (W/ m^{2}K)

The first three properties are measured directly from the system. Overall heat transfer coefficient on the other hand involves dimensional analysis, which could be complex and time consuming and is therefore out of scope for this guidebook. This problem has however been simplified for auditors by the heat loss tables and curves as illustrated in table 1 and figure 6 respectively

Table 1: Steam pipes heat losses vs temperature *(Source: The Engineering Tool Box)*

Difference between Steam Temperature and Surrounding Air Temperature (°F) (deg C)	Heat Loss *(Btu/h per ft)* *(W/m)*									
	Dimension *(inches)*									
	1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3	4	6
100 55.6	56 53.8	68 65.4	82 78.8	107 103	113 109	138 133	163 157	194 186	243 234	337 324
120 66.7	71 68.2	85 81.7	104 99.9	127 122	142 136	175 168	206 198	246 236	308 296	427 410
140 77.8	86 82.6	104 99.9	127 122	155 149	173 166	212 204	251 241	300 288	375 360	521 501
160 88.9	103 99	125 120	152 146	186 179	213 205	256 246	301 289	360 346	451 433	626 602
180 100	121 116	146 140	176 169	217 209	243 234	297 285	351 337	417 401	522 502	725 697
200 111	139 134	171 164	206 198	251 241	282 271	346 333	408 392	488 469	622 598	850 817
225 125	166 160	199 191	243 234	297 285	334 321	410 394	483 464	578 555	726 698	1009 970
250 139	192 185	233 224	284 273	347 333	389 374	478 459	563 541	674 648	849 816	1180 1134
275 153	220 211	266 256	326 313	398 382	447 430	550 529	649 624	778 748	978 940	1360 1307
300 167	251 241	304 292	372 358	455 437	510 490	628 604	742 713	888 853	1140 1096	1557 1496
325 181	285 274	343 330	425 408	520 500	580 557	705 678	843 810	1010 971	1240 1192	1730 1663
350 194	322 309	388 373	480 461	590 567	660 634	790 759	945 908	1130 1086	1358 1305	1930 1855

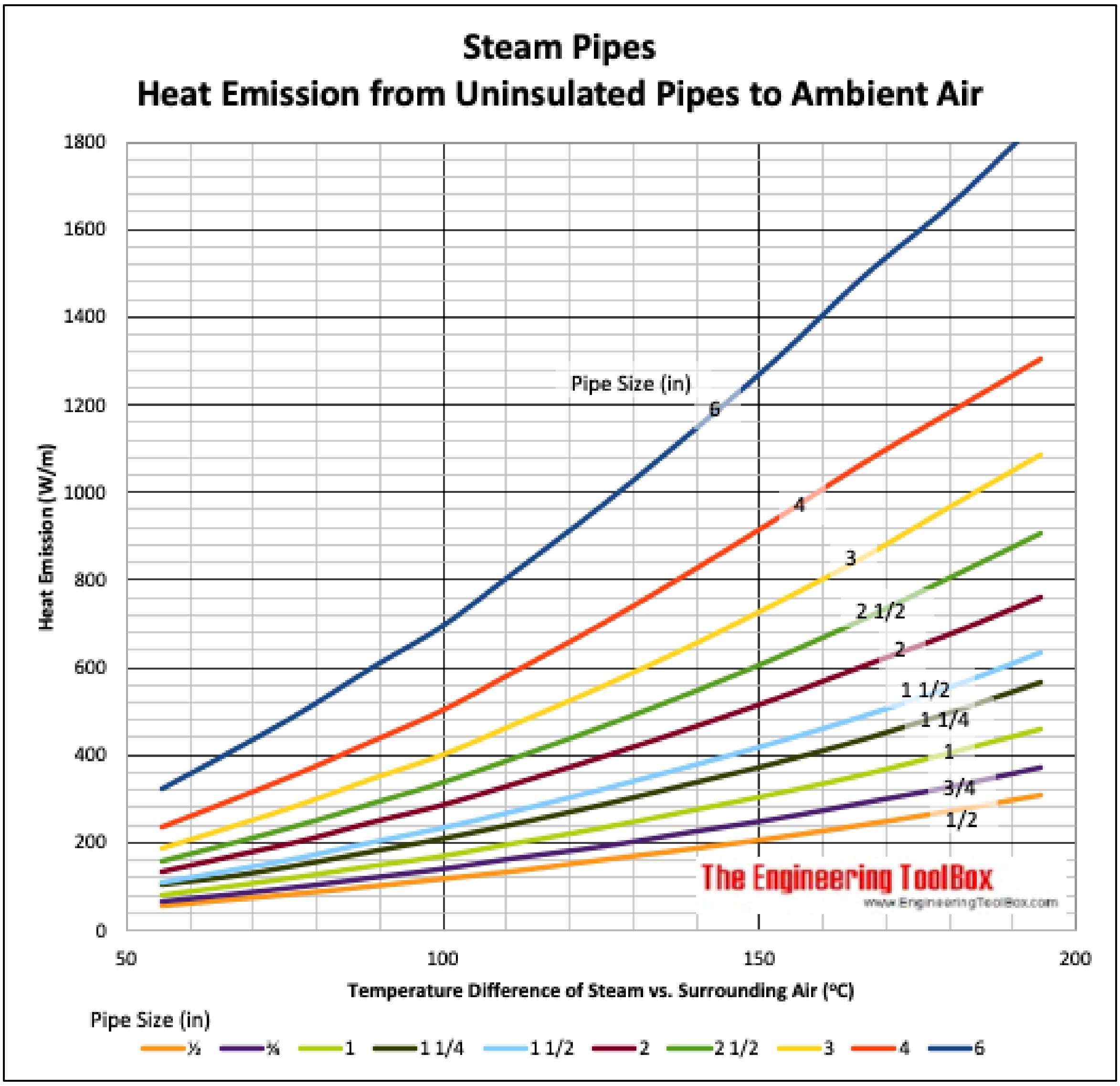


Figure 6: Steam pipes heat losses vs temperature curves (*Source: The Engineering ToolBox)*

With these aids, auditor can easily read off the heat loss per meter due to uninsulated pipes.

We can consider the following example:

Absolute saturated steam pressure at 12 bars Length 5m Diameter 75mm (3 Inches) Surface temperature 88 ^{0}C

The steam temperature of saturated steam at 12 bars should be obtained from the steam tables.
Temperature of saturated steam at 12 bars is 188 ^{0}C.
The difference between steam and surface temperature is 100 ^{0}C
According to the table, the heat loss per meter for the 3-inch pipe is 401 W/m
For 5m therefore the heat loss is 2,005 W
Assuming the steam system operates of 7,000 hrs per year, the total energy loss is
$7{,}000 \times 2{,}005 = 14{,}035$ kWh
This heat loss value is not an end in itself. The auditor should demonstrate how this translates to the loss of primary energy and the related costs. The approach of doing this was provided in the previous example for load matching analysis.
There are situations where the measured temperature difference value is not present in the table. For such a situation, the auditor should interpolate.

The steam generated from the boiler should be used wholly conveyed to the point of use as much as possible. Sometimes, due to maintenance issues, there might be instances of steam leaks in the steam system. The auditor should identify them and compute the related energy losses. The following variables should be used for this analysis:

i. Steam pressure (bars)
ii. Hole size (mm)
iii. Operating time

The hole size can be determined using the travelling microscope and should be done when the steam has been switched off. In case switching off interferes with operations, this can be done during maintenance day. Once the three variables have been obtained, they can be used to determine the energy losses by reading off published tables. Table 2 shows the annual losses due to steam leak.

Table 2: The annual losses due to steam leak (Source. *Marks' Standard Handbook for Mechanical Engineers, 12th edition*)

	Energy Lost at Leak (GJ/yr) at 8760 operating hours per year			
Hole Size (mm)	**Steam Pressure (bar)**			
	3.4	**6.9**	**10.3**	**13.8**
3.2	200	342	478	609
6.4	798	1 367	1 911	2 434
9.5	1 796	3 076	4 299	5 478
12.7	3 192	5 468	7 643	9 738
19.1	7 182	12 303	17 196	21 910
25.4	12 768	21 871	30 571	38 952

Let us discuss the following examples:

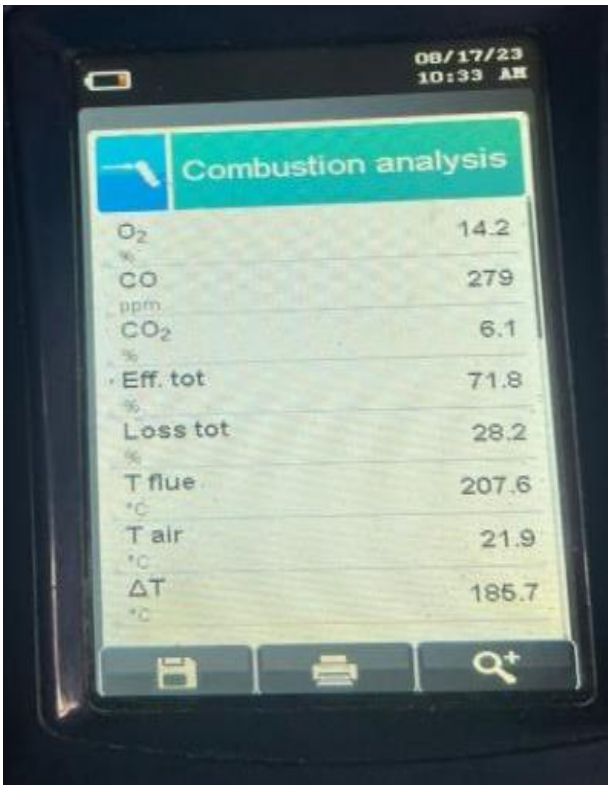
Steam pressure at 10.3 bars
Diameter 9.5 mm
Operating time 7000 hrs
According to the table, the annual energy loss is 4299 GJ/yr. at operation time of 8760 hours. For 7000 hours, we apply proportionality as follows:
7000/8760 × 4299 GJ/yr. = 3435.3 GJ/yr.
Similarly, as in previous example, the auditor should translate this result to primary energy supply to the boiler and the cost.
There are situations where the measured diameter values of the hole are not present in the steam leak heat loss table. For such a situation, the auditor should interpolate.

Energy performance analysis at the stack offers an indication of combustion performance. The following should be points of interest when auditing the section:

i. Flue gas analysis
ii. Stack surface temperature

iii. Ash analysis

Flue gas analysis is done using the combustion analyser. Through this analysis, one can get; combustion efficiency, excess air or oxygen, and flue gas temperature. The auditor should be able to make inferences and establish is operating optimally. Figure 7 shows a side by side presentation of onscreen and print out of flue gas analysis results.



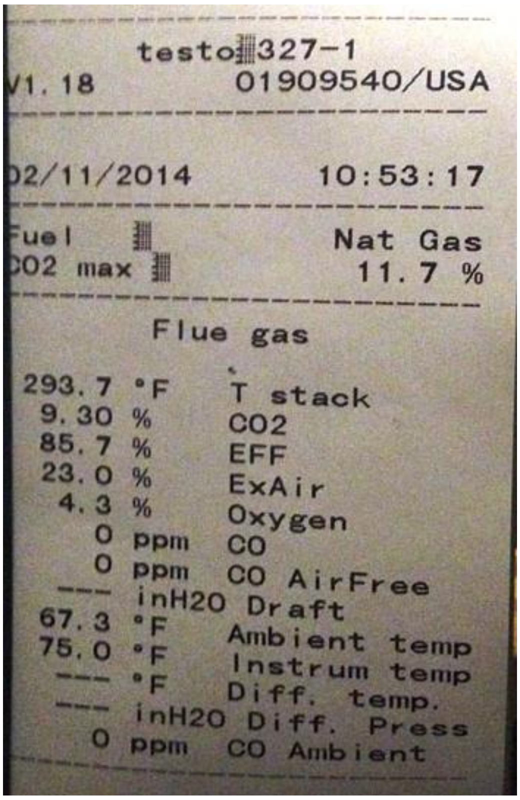


Figure 7: onscreen and print out of flue gas analysis results

The onscreen results in figure 7 represent combustion of a biomass boiler while those on the print out are for a natural gas boiler.

The auditor should compare the results against the standard expected values to make inference about the combustion performance of the boiler. Each fuel type has a unique standard requirement for optimal combustion.

From figure 7, the excess air read from the print out is 23.0%. The results on the screen do not indicate the excess air. In this instance the auditor should use the percentage of oxygen to determine the excess air. In this example, the excess air is determined as follows:

$$excess\ air = \frac{Measured\ \%\ O_2}{21 - Measured\ \%\ O_2} = \frac{14.2}{21 - 14.2} \times 100 = 208.8\%$$

The recommended excess air for natural gas boiler is 10%. Compared to the measure values indicated in figure 7, there are opportunities for combustion performance improvement. Some of the possible reasons for this discrepancy are:

i. An oversized combustion air fan
ii. Poor supply of natural gas. The natural gas injector could be poorly tuned leading to less supply of the required gas.

For the woody biomass boiler, the recommended excess air is 75%. The onscreen measurements show that there is 208.8%. This can be an indication of:

i. Oversized fan
ii. Under supply of wood in the boiler
iii. Poor mixing of the wood fuel and air. This can be as a result of feeding big logs of wood in the boiler. This reduces the combustion surface area.

Normally, excess air in a combustion process shows that the combustion is complete. However, in the biomass boiler example, there are traces of CO, an indicator of incomplete combustion. This thus obviates the possibility of the system having an oversized fan and under supply of wood in the boiler. The focus should be on increasing the combustion surface area, amount and quality of the logs of wood.

In steam systems, there might be cases where heat recovery could improve the overall system efficiency. This can be achieved through recovering heat from the stack or the condensate. The former can be achieved by the use of an economizer or a recuperator, while the latter can be achieved through a flash steam recovery tank. It should, however, be noted that flue gas heat recovery should be the last efficiency option when auditing a steam system. Normally, flue gas temperature should be within the acceptable ranges once the efficiency issues discussed in the previous sections of this volume have been addressed.

The acceptable flue gas temperature ranges for different non-condensing boilers are as illustrated in Table 3.

Table 3: Acceptable Temperature Ranges for Different Fuels.

Fuel	**Acceptable temperature ranges (^oC)**	**Desired temperature after heat recovery (^oC)**
Wood	180-250	180
Industrial Diesel Oil	120-200	120

Natural Gas	120 – 150	120
Heavy Fuel Oil	120 - 200	120

Any boiler system with stack temperatures above these ranges -with all other factors addressed- is a candidate for heat recovery.

Whereas the process of designing a heat recovery system is beyond the scope of this guidebook, energy auditors should be able to quantify potential recoverable heat from the system. Figure 8 shows a boiler with a heat recovery system.

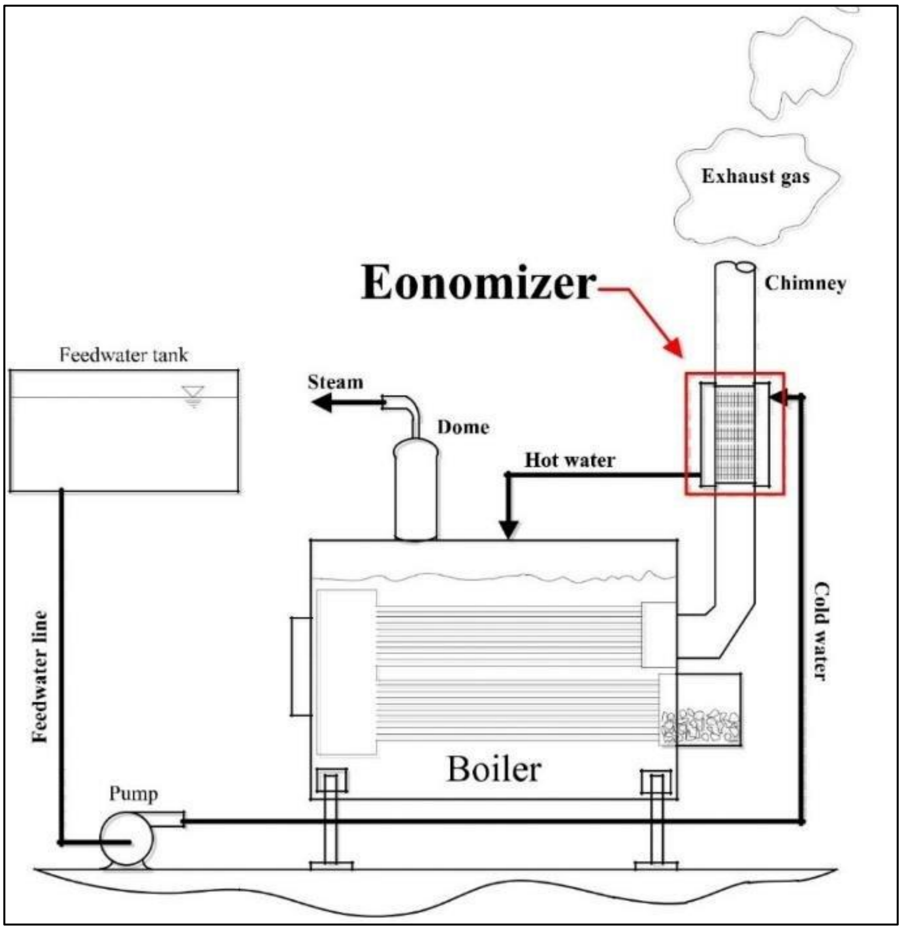


Figure 8: Boiler with heat recovery system

Let us consider the following example.

An Energy auditor measured the stack temperature of an HFO boiler and obtained 385 ° C. To design a flue gas heat recovery system, the temperature after heat recovery must be constrained to the desired temperatures as illustrated in Table 3. This is to avoid corrosion due to the formation of acids. The maximum heat that can be recovered is determined by the flow rate of flue gas, its specific heat capacity and the temperature difference between inlet and outlet as indicated in equation 4.

$$Q = mc_p\Delta\theta \qquad (4)$$

Where;

Q	Potential energy recovered
m	Mass flow rate
c_p	Specific heat capacity
$\Delta\theta$	Temperature change

It is practically impossible to measure the mass flow rate. The energy auditor should measure the volumetric flow rate and multiply it with the density of the fluid to obtain the mass flow rate.
Example;
Consider the following measurements;
Flue gas flowrate = 40000 L/S
Flue gas Temperature = 385°C
Desired Exit Flue Gas Temp = 120°C

Inlet water temperature = 23°C
Desired output temperature of water = 40°C
Mass flow rate?

$$m = volumetric\ flow\ rate\ \times density$$
$$= \frac{40000l}{S} \times \frac{0.525}{1000} = 21\ kg/s$$
$$Q = 21 \times 1.03 \times 265 = 5131.95kJ/s$$

Calculating the quantity of water;

$$m_w = \frac{5131.95}{4.2 \times 17} = 780.28l/s$$

From the example, the amount of heat recovered and the water flow rate are used to size the economizer. The heat recovered will be used to compute the amount of fuel saved and the associated financial savings.

Heat recovery can be achieved by suddenly changing condensate from high pressure to low pressure. This sudden change in pressure results in the formation of flash steam. This flash steam contains thermal energy that would otherwise be wasted if vented into the atmosphere. The heat can be recovered through a flash steam recovery tank or a deaerator. The recovered thermal energy can be used to preheat water or air.
Figure 9 is an illustration of a Temperature enthalpy (T-s) diagram showing steam flashing process.

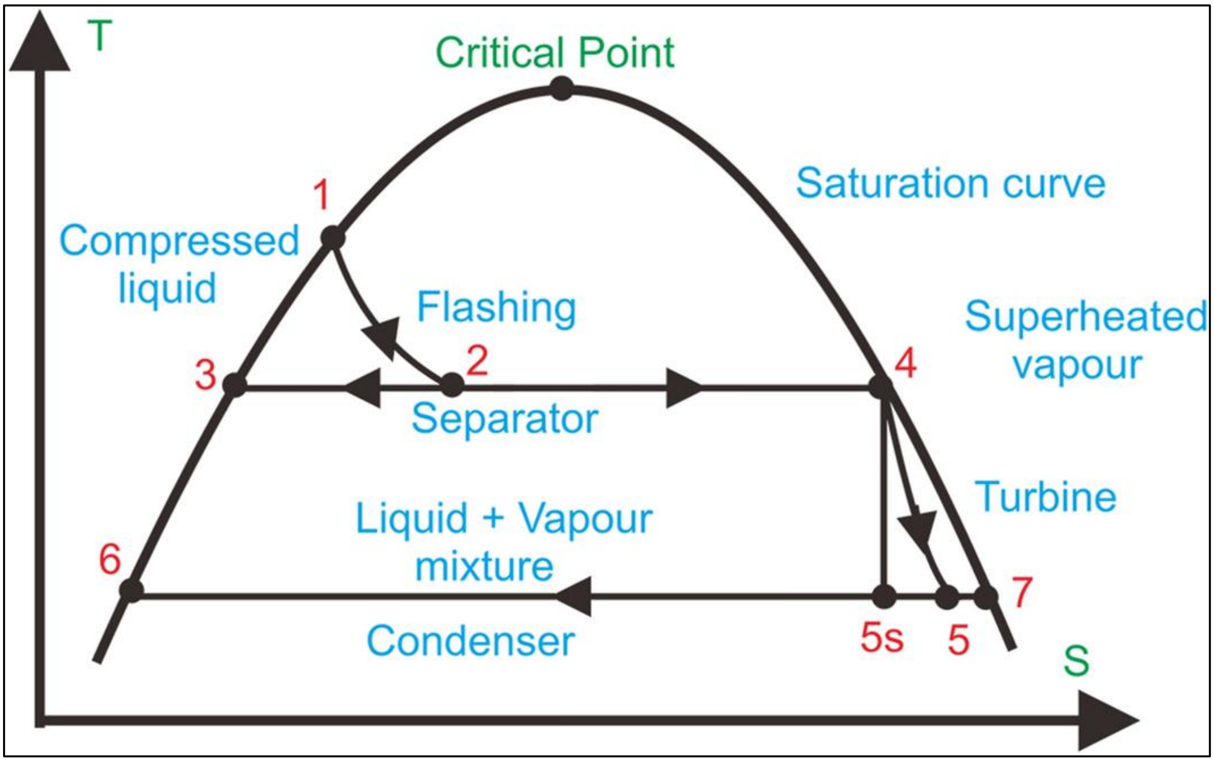


Figure 9: Temperature Enthalpy Diagram (T-s)

From the illustration;

Point	Description	Enthalpy
1	High-pressure condensate	h_1
2	Low pressure (flash steam and water)	h_2
3	Latent heat of vaporization at low pressure	h_{fg}

Using equation 5, the auditor can calculate the ratio of flash steam in the system

$$ratio = \frac{h_2 - h_3}{h_{fg}} \qquad (5)$$

Consider the following example

Boiler capacity = 8000 kg/hr

Operation pressure = 10 bars

To calculate the proportion of flash steam that is present from the reduction of pressure from 10 bars to 4 bars we use equation 5;

From the steam tables

h_2 at 10 bars = 763kJ/kg

h_3 at 4 bars = 605kJ/kg

h_{fg} at 4 bars = 2134kJ/kg

$$= \frac{(763 - 605)}{2134}$$

$$= 0.0754$$

This translates to 7.54% of the condensate water, which changes into steam after flashing.

To calculate the expected heat to be recovered, we first calculate the mass of flash steam generated per hour.

Mass of flash steam = the proportion of the flash steam × boiler capacity.

= 0.0754×8000

=603.2kg/hr

Heat recovered from the flash steam = flash steam mass flow rate × latent heat of vaporization at 4 bars (hfg at 4 bars)

=603.2×2134

=1,287,229 kJ/hr

From the heat recovered, we can calculate the amount of fuel saved and the associated financial savings.

Consider the example below of an illustration of the direct method system

Example

A facility whose operation cycle is 12 hours has a 20,000 kg/h *(20 TPH)* boiler. The boiler runs on heavy fuel oil (HFO). The steam flow is measured by a digital steam flow meter. During an energy audit, the following information was recorded:

i. Average steam pressure over 12 hours = 9.0 bars (absolute)
ii. Average steam Temperature at manifold over 12 hours = 174.5^{0}C
iii. Average feed condensate temperature over 12 hours = 120.0^{0}C
iv. Atmospheric pressure = 1.0 bars
v. Steam demand profile is shown in table 5
vi. Fuel consumption in 12 hours =19,869.90 litres
vii. The density of HFO = 0.9 kg/m^3
viii. Calorific value of HFO = 40.9 MJ/kg

Table 5: Steam demand profile

Time (hour)	Steam Demand in tonnes/h	%Steam demand	Total prodin (30min)	Required production (30 min)	Capacity Factor
7.0	0.8	5.0	0.4	10	4.0
7.3	0.8	5.0	0.4	10	4.0
8.0	5.6	35.0	2.8	10	28.0
8.3	6.4	40.0	3.2	10	32.0
9.0	8.0	50.0	4	10	40.0
9.3	8.8	55.0	4.4	10	44.0
10.3	8.8	55.0	4.4	10	44.0
11.0	9.6	60.0	4.8	10	48.0
11.3	11.2	70.0	5.6	10	56.0
12.0	12.8	80.0	6.4	10	64.0
12.3	13.6	85.0	6.8	10	68.0
13.0	13.6	85.0	6.8	10	68.0
13.3	13.6	85.0	6.8	10	68.0
14.0	13.1	82.0	6.56	10	65.6
14.3	12.0	75.0	6	10	60.0
15.0	9.6	60.0	4.8	10	48.0
15.3	9.6	60.0	4.8	10	48.0
16.0	8.8	55.0	4.4	10	44.0
16.3	8.8	55.0	4.4	10	44.0
17.0	9.6	60.0	4.8	10	48.0
17.3	9.6	60.0	4.8	10	48.0
18.0	4.8	30.0	2.4	10	24.0
18.3	3.2	20.0	1.6	10	16.0
19.0	0.6	4.0	0.32	10	3.2
Total			**101.68**	**240**	**42.4**

Analysis

In this case, it is recommended to plot a steam demand versus time graph. This provides a visual representation of the load profile of the system.

Figure 10 shows the steam demand profile of the facility.

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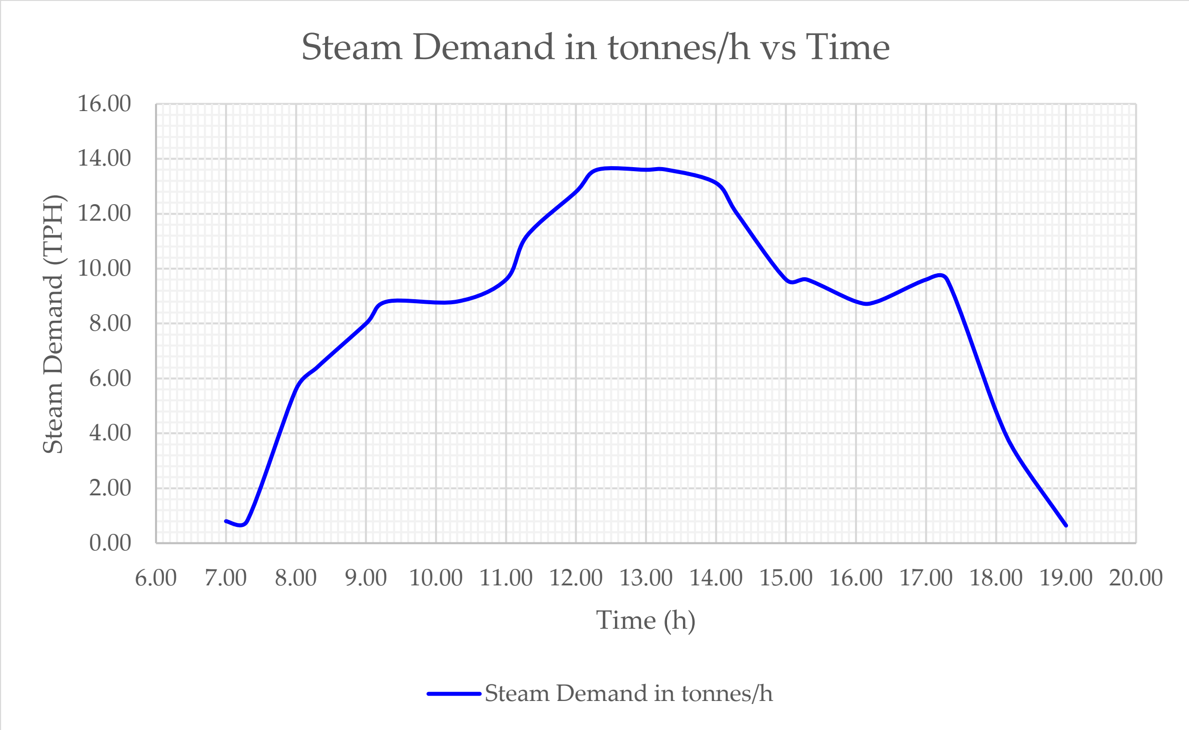

Figure 10: The Steam Demand Profile

As illustrated in Figure 10, the steam demand varies over time. For 8 hours, the steam demand is below 10 tonnes per hour, indicating under-utilization of the steam system.

From the steam demand profile in Table 5, the total steam produced in 12 hours is 101.68 tonnes, which results to an average of 8.47 tonnes per hour.
Total fuel consumed in kg for 12 hours

=19,869.90 litres × 0.9 kg/litre

= 17,882.91kg

Enthalpy at 9 bars = 2,772.52 kJ/kg

Enthalpy of water at 120^{0}C = 503.302 kJ/kg

From equation 1

$$Boiler\ thermal\ efficiency, \eta\ (\%) = \frac{101{,}680 \times (2772.52 - 503.302)}{17{,}882.91\ \times 40.9\ \times 1000} \times 100$$
$$= \mathbf{31.55}\%$$

Boiler capacity factors

In a period of 12 hours, the boiler produced 101,680 kg of steam, while it is expected to produce 12 x 20,000 = 240,000 kg.

Capacity factor = 101,680/240,000 = **42.42%**

From the calculation, the steam system efficiency of 31.55% and a capacity factor of 42.42% are relatively low. The recommended industrial efficiency and capacity factor of such a system is above 80% and 75%, respectively.

Discussions and recommendations

From the results of the boiler energy audits, it can be observed that:

i. For more than 8 hours, the boiler operates at less than 50% of the rated capacity. This will negatively affect the efficiency of the boiler steam systems. There is a need to have a smaller boiler installed to cater for smaller loads.

ii. The condensate returns at an average temperature of 120 ° C. The auditor should recommend to the facility to explore ways of extracting heat from condensate water.

Calculation of the energy efficiency measures

From the energy audit it can be observed that one of energy efficiency measures is load marching, where the efficiency of the boiler steam system can have increased by using a small boiler. The small boiler should be able to meet the requirements at least 8 hours when the steam requirements is at least less than 10,000 kg/h.

To implement this project, calculations of energy savings should be done by assuming an increase of efficiency from 31.55 % to 75%. The boiler running hours can be assumed to be 7 hours, to be pessimistic.

Calculations

Fuel currently consumed in 7 hours = 17,882.91 x 7/12 =10,431. 7 kg

Fuel savings can be calculated using equation 6

$$FS = FC_{ob} - FC_{nb} \qquad (6)$$

Assuming 20,000 kg/h boilers operating at an efficiency of 31.55%, fuel consumption in 7 hours is 10,431.71 kg.

For 10,000 kg boiler fuel consumption will be calculated by equation 7:

$$FC_{nb} = \frac{SFR \times (h_s - h_w)}{FGCV \times \eta} \times RH \qquad (7)$$

$$FC_{nb} = \frac{10,000 \times (2772.2 - 503.302)}{40.9 \times 0.75 \times 1000} \times 7 = 5,177.6\ kg$$

Energy savings

$$FS = 10,431.71 - 5,177.6 = 5,254.1\ kg$$

Financial savings or cost savings (CS)

$$CS = FS \times FC \qquad (8)$$

$$CS = 5,254.1 \times 110 = KSh\ 577,950$$

Assuming the boiler's steam system operates for 300 days per year.
Annual financial savings are 577,590 x 300 = KSh 173,385,239

Assume the cost of buying and installing the 10TPH boiler is KSh 11,000,000

$$Simple\ Payback\ (SPB) = \frac{Investment}{Annual\ savings\ (or\ savings\ )} \qquad (9)$$

$$SPB = \frac{11,000,000}{173,385,239} = 0.06\ years$$

The simple payback period is less than one month.