This online textbook provides free access to a comprehensive education and training package that brings together the knowledge of how countries, specifically Australia, can achieve at least 60 percent cuts to greenhouse gas emissions by 2050. This resource has been developed in line with the activities of the CSIRO Energy Transformed Flagship research program, which is focused on research that will assist Australia to achieve this target. This training package provides industry, governments, business and households with the knowledge they need to realise at least 30 percent energy efficiency savings in the short term while providing a strong basis for further improvement. It also provides an updated overview of advances in low carbon technologies, renewable energy and sustainable transport to help achieve a sustainable energy future. While this education and training package has an Australian focus, it outlines sustainable energy strategies and provides links to numerous online reports which will assist climate change mitigation efforts globally.

CHAPTER 3: ENERGY EFFICIENCY OPPORTUNITIES FOR INDUSTRIAL USERS

LECTURE 3.2: OPPORTUNITIES FOR IMPROVING THE EFFICIENCY OF BOILER AND STEAM DISTRIBUTION SYSTEMS
The Work was produced by The Natural Edge Project using funds provided by CSIRO and the National Framework for Energy Efficiency. The development of this publication has been supported by the contribution of non-staff related on-costs and administrative support by the Centre for Environment and Systems Research (CESR) at Griffith University, under the supervision of Professor Bofu Yu, and both the Fenner School of Environment and Society and Engineering Department at the Australian National University, under the supervision of Professor Stephen Dovers. The lead expert reviewers for the overall Work were: Adjunct Professor Alan Pears, Royal Melbourne Institute of Technology; Geoff Andrews, Director, GenesisAuto; and Dr Mike Dennis, Australian National University.

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The International Energy Agency forecasts that if policies remain unchanged, world energy demand is set to increase by over 50 percent between now and 2030.\(^1\) In Australia, CSIRO has projected that demand for electricity will double by 2020.\(^2\) At the same time, The Intergovernmental Panel on Climate Change (IPCC) has warned since 1988 that nations need to stabilise their concentrations of CO\(_2\) equivalent emissions, requiring significant reductions in the order of 60 percent or more by 2050.\(^3\) This portfolio has been developed in line with the activities of the CSIRO Energy Transformed Flagship research program; ‘the goal of Energy Transformed is to facilitate the development and implementation of stationary and transport technologies so as to halve greenhouse gas emissions, double the efficiency of the nation’s new energy generation, supply and end use, and to position Australia for a future hydrogen economy’.\(^4\) There is now unprecedented global interest in energy efficiency and low carbon technology approaches to achieve rapid reductions to greenhouse gas emissions while providing better energy services to meet industry and society’s needs. More and more companies and governments around the world are seeing the need to play their part in reducing greenhouse gas emissions and are now committing to progressive targets to reduce greenhouse gas emissions. This portfolio, *The Sustainable Energy Solutions Portfolio*, provides a base capacity-building training program that is supported by various findings from a number of leading publications and reports to prepare engineers/designers/technicians/facilities managers/architects etc. to assist industry and society rapidly mitigate climate change.

The Portfolio is developed in three modules;

**Module A: Understanding, Identifying and Implementing Energy Efficiency Opportunities for Industrial/Commercial Users – By Technology**

*Chapter 1: Climate Change Mitigation in Australia’s Energy Sector*

Lecture 1.1: Achieving a 60 percent Reduction in Greenhouse Gas Emissions by 2050
Lecture 1.2: Carbon Down, Profits Up – Multiple Benefits for Australia of Energy Efficiency
Lecture 1.3: Integrated Approaches to Energy Efficiency and Low Carbon Technologies
Lecture 1.4: A Whole Systems Approach to Energy Efficiency in New and Existing Systems

*Chapter 2: Energy Efficiency Opportunities for Commercial Users*

Lecture 2.1: The Importance and Benefits of a Front-Loaded Design Process
Lecture 2.2: Opportunities for Energy Efficiency in Commercial Buildings
Lecture 2.3: Opportunities for Improving the Efficiency of HVAC Systems

*Chapter 3: Energy Efficiency Opportunities for Industrial Users*

Lecture 3.1: Opportunities for Improving the Efficiency of Motor Systems
Lecture 3.2: Opportunities for Improving the Efficiency of Boiler and Steam Distribution Systems
Lecture 3.3: Energy Efficiency Improvements available through Co-Generation

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Module B: Understanding, Identifying and Implementing Energy Efficiency Opportunities for Industrial/Commercial Users – By Sector

Chapter 4: Responding to Increasing Demand for Electricity
Lecture 4.1: What Factors are Causing Rising Peak and Base Load Electricity Demand in Australia?
Lecture 4.2: Demand Management Approaches to Reduce Rising ‘Peak Load’ Electricity Demand
Lecture 4.3: Demand Management Approaches to Reduce Rising ‘Base Load’ Electricity Demand
Lecture 4.4: Making Energy Efficiency Opportunities a Win-Win for Customers and the Utility: Decoupling Energy Utility Profits from Electricity Sales

Chapter 5: Energy Efficiency Opportunities in Large Energy Using Industry Sectors
Lecture 5.1: Opportunities for Energy Efficiency in the Aluminium, Steel and Cement Sectors
Lecture 5.2: Opportunities for Energy Efficiency in Manufacturing Industries
Lecture 5.3: Opportunities for Energy Efficiency in the IT Industry and Services Sector

Chapter 6: Energy Efficiency Opportunities in Light Industry/Commercial Sectors
Lecture 6.1: Opportunities for Energy Efficiency in the Tourism and Hospitality Sectors
Lecture 6.2: Opportunities for Energy Efficiency in the Food Processing and Retail Sector
Lecture 6.3: Opportunities for Energy Efficiency in the Fast Food Industry

Module C: Integrated Approaches to Energy Efficiency and Low Emissions Electricity, Transport and Distributed Energy

Chapter 7: Integrated Approaches to Energy Efficiency and Low Emissions Electricity
Lecture 7.1: Opportunities and Technologies to Produce Low Emission Electricity from Fossil Fuels
Lecture 7.2: Can Renewable Energy Supply Peak Electricity Demand?
Lecture 7.3: Can Renewable Energy Supply Base Electricity Demand?
Lecture 7.4: Hidden Benefits of Distributed Generation to Supply Base Electricity Demand

Chapter 8: Integrated Approaches to Energy Efficiency and Transport
Lecture 8.1: Designing a Sustainable Transport Future
Lecture 8.2: Integrated Approaches to Energy Efficiency and Alternative Transport Fuels – Passenger Vehicles
Lecture 8.3: Integrated Approaches to Energy Efficiency and Alternative Transport Fuels - Trucking

Chapter 9: Integrated Approaches to Energy Efficiency and Distributed Energy
Lecture 9.3: Beyond Energy Efficiency and Distributed Energy: Options to Offset Emissions
Energy Efficiency Opportunities for Industrial Users

Lecture 3.2: Opportunities for Improving the Efficiency of Boiler and Steam Distribution Systems

Educational Aim

The aim of this lecture is to cover the key components of design, operation and maintenance for boiler and steam distribution systems. A clear understanding of energy efficiency opportunities will assist engineers and other students of these modules to realise potential energy efficiency improvements in their boiler and similar systems.

Essential Reading

Reference


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5 Peer review by Geoff Andrews - Director, Genesis Now Pty Ltd and Glenn Platt – CSIRO.
Learning Points

1. The basic function in any boiler is to burn fuel and use the heat to boil water and make steam. On an average industrial site, boilers can account for 20-60 percent of energy costs and represents about 35 percent of all potential energy efficiency improvements. Without comprehensive operations and maintenance management, energy consumption in a boiler can increase by 10-20 percent.

2. Energy transfer through the boiler system is both in series and in closed-loops. That is, energy is transferred in series: 1) from the fuel, 2) to the boiler, 3) to the distribution system to the end use; and also in closed-loops from both 4) the boiler stack, and 5) the distribution system back to the boiler input.

3. Load management: Boiler energy efficiency can be improved by providing steam only where lower temperature water is not suitable, and by implementing a load management strategy for bringing online and taking offline the right-sized boilers to match loads. Control technologies assist effective load management.

4. Key areas where energy efficiency opportunities exist include:
   - **Steam pressure**: In designing the boiler, multiple combinations of pipe cost, pipe losses, latent heat, fuel requirement and stack losses must be tested to determine the optimal pipe size. Typically, the optimal delivered steam pressure is the lowest pressure that meets the highest pressure demand.
   - **Fuel selection**: Some boilers can operate on a variety of fuels. Favouring fuels such as natural gas, waste fuels and biomass can reduce greenhouse gas emissions while improving the overall energy efficiency of the plant.
   - **Combustion efficiency**: Combustion efficiency is maximised by optimising excess air and developing combustion uniformity. Both too little and too much excess air affects boiler energy efficiency and levels of pollution emissions. Complete and uniform combustion requires a uniform fuel-air mixture and, in multi-burner boilers, having all burners functioning effectively. Analysers and ‘oxygen trim’ control systems assist in optimising excess air and developing a uniform fuel-air mixture.
   - **Tube fouling**: Fire-side fouling occurs when soot accumulates on the fire side of the tubes. Water-side fouling occurs when chemical compounds in the water accumulate on the water surface.

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side of the tubes (called scaling). Accumulated solids act as insulation and prevent heat transfer between the fire and water. Soot is removed relatively easily by simple brushing using a low- or high-pressure soot blower and vacuum cleaner. Removing scale is more difficult and is usually by mechanical means, acid cleaning or water treatment.

- Standby losses: Standby losses are heat losses to the surroundings that occur whenever the boiler is online. When the boiler skin temperature is at steady state, standby losses are about 1.5-2 percent of the rated boiler capacity regardless of the load. The effect of standby losses can be minimised through load management and good insulation. Insulation prevents heat loss to the surroundings hence improving energy efficiency. The first 2.5 cm of insulation reduces heat loss by about 90 percent. Typically, insulating all surfaces – boiler, process vessels, distribution pipes, valves, flanges, fittings and steam traps – that are above 50°C is cost effective.

- Leaks: Heat losses occur rapidly through air leaks. Air leaks also interfere with combustion analyser readings and control system calculations, and hence may encourage inappropriate corrective action that can reduce energy efficiency. Air leaks in the boiler are identified using smoke sticks, butane flames or ultrasonic probes. Steam leaks occur through faulty valves, joints, steam traps, pipes and flexible hoses and can result in substantial reduction in energy efficiency and increase in cost.

5. Distribution system design: A modular pipe circuit with upstream valves can reduce pipe losses by taking offline sections that are not required to distribute steam. Heat loss through pipes is proportional to pipe length and can hence be reduced by using short straight pipes. The distribution system energy efficiency can also be increased by using energy efficient motor-pump systems.

6. Condensate recovery: Heat transfer from steam forms condensate, which inhibits further heat transfer from the steam where required. Steam traps are used to remove condensate and incondensable gases, such as air, from the distribution system whilst allowing dry steam to pass. Condensate return systems reduce energy, water and chemical consumption by redirecting condensate collected by steam traps to the boiler input.

19 Ibid, p 5.
20 Ibid.
21 Ibid, p 5.
22 Ibid, p 3.
23 Ibid, p 3.
24 Ibid, p 3.
26 Ibid, p 3.
7. *Heat recovery.* Heat loss from stack gas, equivalent to 15-20 percent of the fuel energy, usually represents the largest source of inefficiency. Stack gas can be redirected into either an economiser, which transfers heat to boiler input water, or a pre-heater, which transfers heat into the boiler input air. Blowdown effluent, usually four to eight percent of total steam volume produced, can be redirected into heat exchangers that transfer the heat to boiler input water. End use fluid heat can be redirected into a shell and tube heat recovery unit, which can transfer heat to boiler input water with up to 80-90 percent efficiency.

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28 Ibid.
Brief Background Information

Boilers are used to produce steam. The basic function in any boiler is to burn fuel and use the heat to boil water and make steam. On an average industrial site, boilers can account for 20-60 percent of energy costs. The main benefits of supplying heat through steam are that: a) steam stores a relatively high amount of heat, and b) steam transfers heat at a constant temperature for a given pressure. On an average industrial site, steam can account for about 35 percent of all potential energy efficiency improvements. Boilers are designed to produce steam at either low pressure (700–1400 kPa) or high pressure (>4200 kPa). Low pressure steam is used for heating and as a heat exchange fluid. High pressure steam is used to drive mechanical equipment such as turbines and reciprocating engines. There are two conventional types of boilers: Water Tube boilers and Fire Tube boilers.

![Image of Water Tube Boiler](image1)

![Image of Fire Tube Boiler](image2)

**Figure 3.2.1.** (a) Water Tube Boiler; (b) Fire Tube Boiler.

*Source: HowStuffWorks*

Water Tube boilers, where water circulates through tubes and is heated by surrounding combustion, are usually used in large heat energy applications. Fire Tube boilers, where combustion occurs in tubes while water is circulated around the tubes, are generally smaller and more common and are usually used in lower energy applications. An increasingly popular type of modern boiler is the condensing boiler. Condensing boilers function similarly to water tube boilers and fire tube boilers, and incorporate an additional heat exchanger so that the hot exhaust gases lose much of their energy to pre-heat the water in the boiler system (see Heat Recovery). Condensing boilers demonstrate energy efficiencies of up to 95 percent. Without comprehensive operations and maintenance management, energy consumption in a boiler can increase by 10-20 percent.

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31 Ibid.
32 Ibid.
Whole System Design (WSD) Approach – Compounding Benefits

The remainder of this lecture describes potential energy efficiency improvements for the component systems of a boiler system, which incorporates both a boiler and its distribution system. It is important to note that efficiency improvements in a system amass to an improvement greater than the arithmetic sum of the individual improvements. In the case of a boiler system, energy transfer through the component systems is both in series and in closed-loops. That is, energy is transferred in series: 1) from the fuel, 2) to the boiler, 3) to the distribution system to the end use; and also in closed-loops from both 4) the boiler stack 5) and distribution system back to the boiler input. Reducing end use load by 10 percent will also reduce the load on every component system upstream (the whole boiler system) by 10 percent. Improving also the efficiency of the distribution system by 10 percent will not affect the downstream end use load, but will reduce the load on every component system upstream by a further 10 percent. Continuing efficiency improvements upstream, each increment compounds with the previous increments. The result is that instead of consuming 90 percent of the energy that a typical boiler system would consume, the efficient boiler system (with three efficient component subsystems in series) consumes only 73 percent of the energy, a saving of 17 percent.

For systems with component subsystems in series, a downstream to upstream sequence is optimal for enabling efficiency improvements, which is opposite to the sequence that component systems are presented in here. In addition to the series improvements, returning 10 percent of the energy from the distribution system to the boiler input (equivalent function to fuel) will reduce the demand for fuel by 10 percent. Returning also 10 percent of the energy from the boiler stack to the boiler input will reduce the demand for fuel by a further 10 percent. The new result is that the efficient boiler consumes only 59 percent (i.e. 0.95) of the energy that a typical boiler system would consume. For systems with closed-loop energy transfers, an iterative downstream to upstream sequence (measured from the source) is optimal for enabling each closed-loop efficiency improvement.

Load Management

Not all heating and high pressure applications require steam. Replacing steam with hot water where suitable will reduce energy consumption by reducing the required boiler water output temperature. The required steam loads on a site can vary as often as every few hours. On sites with several loads and boilers, fewer boilers operating at higher loads is generally more energy efficient than all boilers operating at lower loads. A load management strategy for bringing online and taking offline the right-sized boilers to match the required loads can greatly increase energy efficiency. Most boilers have peak efficiency somewhere between 60 and 90 percent of load. Boilers with large standby losses (see Standby Losses), for reasons such as insufficient insulation (see Insulation), will lose about the same amount of heat regardless of load and thus are more efficient at high loads. Boilers with small radiation heat losses are more efficient at lower loads. Favouring the most efficient boilers assists in maximising energy efficiency, and control technologies assist effective load management. Intelligent control technologies can be used to automatically select the boiler and adjust the fuel feed.

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to match the load. Simpler technologies such as shutdown timers can be used to take offline the boilers that become unloaded.

**Steam Pressure**

The optimal delivered steam pressure is determined by considering several factors. Increasing the steam pressure reduces pipe sizes and subsequent heat losses but also reduces the available latent heat, increases the fuel requirement, and increases subsequent heat losses through the stack (chimney). In designing the boiler, multiple combinations of pipe cost, pipe losses, latent heat, fuel requirement and stack losses must be tested to determine the optimal pipe size. Typically, the optimal delivered steam pressure is the lowest pressure that meets the highest pressure demand.

**Fuel Selection**

Some boilers can operate on a variety of fuels. Favouring fuels such natural gas, waste fuels and biomass can reduce greenhouse gas emissions while improving overall energy efficiency of the plant.

**Combustion Efficiency**

Stable combustion requires fuel, oxygen and an ignition source. Fuels that become the ignition source themselves reduce energy consumption by allowing the original ignition source to be shut down. Complete combustion forms carbon dioxide (CO$_2$), water, oxides of sulphur (SO$_X$) and oxides of nitrogen (NO$_X$). Combustion efficiency is maximised by optimising excess air and developing combustion uniformity. The theoretical quantity of oxygen required for complete combustion of a fuel is called the stoichiometric (theoretical) air. In practice, combustion conditions are never ideal and additional oxygen, called excess air, is required. Both too little and too much excess air affects boiler energy efficiency and pollution emissions. Thus it is important to optimise the excess air input to the boiler. Figure 3.2 shows the effect of air input volume into the boiler on stack gas composition. Too little excess air results in incomplete combustion and is better avoided. During incomplete combustion, un-combusted fuel, soot, smoke and carbon monoxide (CO) escape through the boiler stack and cause: fire-side fouling (see Fire-Side Fouling), pollution, a decrease in combustion efficiency, the flame to blow out, and can create the potential for an explosion. In addition, CO formation releases only about one-third of the heat that CO$_2$ formation releases.

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41 Ibid, p 8.


43 Ibid.

44 Ibid.

Additional excess air provides insurance against the effects of incomplete combustion, against variations in fuel composition and against variations in local environmental conditions (such as ambient air pressure and relative humidity). However, too much excess air increases the volume of unused hot gas exhaust through the stack – both nitrogen (\(N_2\)) and excess oxygen (\(O_2\)) travel through the boiler without contributing to the combustion process, but still remove heat. Analysers and control systems can automatically adjust the air-fuel ratio based on continuous measurement of the \(O_2\) in the exhaust gases. The accuracy of excess air input is better in control systems that use variable speed fans rather than fixed speed fans. Inaccurate analyser readings and control system behaviour are usually due to: fresh air leaking (see Leaks) into the system near the analyser; infrequent or incorrect analyser calibration; too little excess air at full load; and/or locating the analysers at a non-representative location.

Complete and uniform combustion requires a uniform fuel-air mixture and, in multi-burner boilers, it also requires all burners to function effectively. A complete assessment of combustion uniformity usually involves monitoring \(O_2\), \(CO_2\) and \(NO_X\) emissions concentrations. A less thorough but usually sufficient assessment involves monitoring \(O_2\) concentration near the stack exhaust or economiser exit. A single malfunctioning burner can greatly reduce energy efficiency.

For optimum boiler operation, the stack temperature is generally less than 65˚C above the steam temperature at the boiler pressure. Every 22˚C increase in stack temperature will decrease energy efficiency by about 1 percent.

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**Fire-Side Fouling**

Fire-side fouling occurs when soot, a soft black solid, accumulates on the fire side of the tubes. Fire-side fouling is unlikely to occur when the fuel is natural gas and combustion efficiency is high. It is likely to occur when the fuel is oil, especially lower grade oil that contains large quantities of alkaline sulphates and vanadium pentoxide, which are compounds that have low fusion temperatures and hence easily slag and deposit on the tubes.\(^5^3\) Fire-side fouling is also likely to occur when the fuel is solid such as coal and wood, which produce ash-based slag and soot.\(^5^4\) If left for too long, the high temperatures can then melt the ash and form an enamel. Accumulated solids act as insulation and prevent heat transfer between the fire and water. The heat instead escapes through the stack and decreases boiler energy efficiency.

To illustrate the cost of fire-side fouling, consider a typical boiler rated at 8 MW, operating at an average load of 4 MW, year round. If the boiler efficiency is 85 percent and the natural gas cost is $4/GJ the annual cost would be $2.35 million. However, a 0.8mm layer of soot reduces boiler efficiency an estimated 2.5 percent, a 3 mm layer an estimated 8.5 percent.\(^5^5\) Therefore, a 1.6 mm layer of soot resulting in 4.5 percent efficiency loss will add $131,500 to annual costs.

Fire-side fouling is relatively easy to clean. Common cleaning procedures include simple brushing, using a low- or high-pressure soot blower\(^5^6\) and using a vacuum cleaner.\(^5^7\) Table 3.2.1 summarises tube cleaning frequency, which is determined by the fuel used.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Cleaning frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>Annually and more often for problematic boilers</td>
</tr>
<tr>
<td>Oil</td>
<td>Monthly</td>
</tr>
<tr>
<td>Solid</td>
<td>Weekly or daily</td>
</tr>
<tr>
<td>Low quality</td>
<td>Up to every shift</td>
</tr>
</tbody>
</table>

*Source: PG&E (1997)\(^5^8\) and Sustainability Victoria (2006)\(^5^9\)

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\(^5^4\) Ibid.


\(^5^7\) Ibid, p 4.


\(^5^9\) Ibid, p 4.
**Water-Side Fouling**

Water-side fouling occurs when chemical compounds in the water accumulate on the water side of the tubes, otherwise known as scaling. Like soot, scaling acts as insulation, only twice as effective,\(^60\) that decreases boiler energy efficiency. In addition, the insulating effect of scaling causes the tube material to overheat, which reduces its operating life.\(^61\) Scaling can be prevented by demineralising the water,\(^62\) pre-treating the water with water softeners and chemicals, and by performing blowdown.\(^63\) Table 3.2.2 shows concentration limits of common chemical compounds in water that are unlikely to cause scaling.

**Table 3.2.2:** Maximum chemical compound concentration limits to prevent scaling

<table>
<thead>
<tr>
<th>Boiler pressure range (kPa gauge)</th>
<th>Total solids (ppm)</th>
<th>Total alkalinity (ppm)</th>
<th>Suspended solids (ppm)</th>
<th>Silica (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2000</td>
<td>3,500</td>
<td>700</td>
<td>300</td>
<td>125</td>
</tr>
<tr>
<td>2000-3100</td>
<td>3,000</td>
<td>600</td>
<td>250</td>
<td>90</td>
</tr>
<tr>
<td>3100-4100</td>
<td>2,500</td>
<td>500</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>4100-5200</td>
<td>2,000</td>
<td>400</td>
<td>100</td>
<td>35</td>
</tr>
<tr>
<td>5200-6200</td>
<td>1,500</td>
<td>300</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>6200-7000</td>
<td>1,250</td>
<td>250</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td>7000-10,300</td>
<td>1,000</td>
<td>200</td>
<td>20</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Source: PG&E (1997)\(^64\)

There are two types of blowdown\(^65\) that are used to remove solids from the water. Skimming blowdown removes light, dissolved solids and is best used as a continuous process. Bottom blowdown, or mud blowdown, removes heavy, settled solids and is best used intermittently.\(^66\) The volume and frequency of blowdown must be optimised against the heat lost through drained hot water, and is best scheduled automatically based on water quality.

Care is required in removing scale by mechanical means, acid cleaning or water treatment.\(^67\) Mechanical and acid cleaning can damage tubes. Water treatment can liberate large pieces of scale that may restrict water flow and subsequently cause localised overheating and possible catastrophic failure.


\(^{64}\) Ibid, p 5.

\(^{65}\) Ibid, p 8.

\(^{66}\) Ibid.

\(^{67}\) Ibid, p 5.
Standby Losses

Standby losses\textsuperscript{66} are heat losses to the surroundings that occur whenever the boiler is online. When the boiler skin temperature is at steady state, standby losses are about 1.5-2 percent of the rated boiler capacity regardless of the load.

...imagine a boiler rated at 10 GJ/hr fuel input, but operating at a 2 GJ/hr level. The standby loss of 2% of 10 GJ/hr is 200 megajoules per hour.

The effect of standby losses can be minimised through effective load management (see Load Management).

Leaks

Typical leaks in boilers and distribution systems are air leaks and steam leaks. Heat losses occur rapidly through air leaks. Air leaks also interfere with combustion analyser readings and control system calculations, and hence may encourage inappropriate corrective action that can reduce energy efficiency. Air leaks in the input line, boiler chamber and stack will change the oxygen (O\textsubscript{2}) concentration and temperature readings.

High oxygen readings caused by air leaks can lead operators to reduce the [excess air], resulting in unburned combustibles (i.e., wasted fuel) in the stack.\textsuperscript{69}

Air leaks in the boiler are identified using smoke sticks, butane flames or ultrasonic probes.\textsuperscript{70} Steam leaks occur through faulty valves, joints, steam traps, pipes and flexible hoses and can result in substantial reduction in energy efficiency and increase in cost.

...a 1 mm diameter hole on a steam line at 700 kPa will result in an annual energy loss equivalent to... 166 GJ [about [AU]$700]... of natural gas per year.\textsuperscript{71}

Monthly inspection targeting of steam leaks is usually sufficient unless abnormal performance is observed.\textsuperscript{72} Steam leaks in the boiler are identified using ultrasonic probes.\textsuperscript{73} Steam leaks in the distribution pipes are usually identified by visual inspection.

Distribution System Design

Boilers, especially centralised boilers, may not require steam to be delivered to all locations at all times. A modular pipe circuit with upstream valves, perhaps in addition to downstream valves, can reduce pipe losses by taking sections offline that are not required to distribute steam. Modular pipe circuits can better provide functional and thermal isolation between sections so energy efficiency can be maintained despite varying load locations and online circuit configurations.\textsuperscript{74} Heat loss through pipes is proportional to pipe length and can hence be reduced by using short straight pipes.


\textsuperscript{68}Ibid, p 3.


3.2.3 estimates heat losses through 1m lengths of uninsulated pipe of varying internal diameters for different pipe temperatures.

![Figure 3.2.3. Estimated heat losses through 1 m lengths of uninsulated pipe of varying internal diameters as a function of temperature. Source: Sustainability Victoria (2006)](image)

The distribution system energy efficiency can be increased by using energy efficient motor-pump systems (see Lecture 3.1: Motor Systems).

**Insulation**

Since boilers and distribution systems operate at high temperatures, heat loss to the surroundings through uninsulated surfaces is high. Insulation\(^{76}\) prevents heat loss and hence improves energy efficiency. The first 25mm of typical insulation reduces heat loss by about 90 percent. Insulating all surfaces – boiler, process vessels, distribution pipes, valves, flanges, fittings and steam traps – that are above 50˚C is usually cost effective. The amount of additional insulation must be optimised against the insulation cost and heat loss. Wet insulation performs poorly and is best replaced. Causes of wet insulation include leaking valves, external piping leaks, tube leaks or leakage from adjacent equipment. Many distribution system components have deceptively high surface areas and thus are sources of substantial heat loss.

In terms of potential heat loss, a flange is equivalent to a 600mm pipe onto which it is fit and a globe valve is equivalent to a 5m pipe onto which it is fit.\(^{77}\) A 15cm gate valve may have a surface area of

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more than 0.5m$^2$. These components are best insulated despite the need to access them regularly. Flexible and removable insulation is available to improve access.

**Condensate Recovery**

Condensate recovery is by steam traps and condensate return systems. Heat transfer from steam forms condensate, which inhibits further heat transfer from the steam where required. Steam traps are used to remove condensate and incondensable gases, such as air, from the distribution system while allowing dry steam to pass. Steam traps collect condensate and incondensable gases for either discharge or reuse through a condensate return system. The function by which steam traps distinguish between steam and other fluid components is either mechanical, thermostatic, thermodynamic or some other function. Each type of steam trap has its advantages and disadvantages so selection is determined by the specific application. Condensate return systems reduce energy, water and chemical consumption by redirecting condensate collected by steam traps to the boiler input. Condensate contains up to 12 percent of the heat and is already pre-treated with water softeners and chemicals. Every 5°C increase in boiler water input temperature will reduce fuel consumption by 0.7 percent.

**Heat Recovery**

The major opportunities for heat recovery are the stack gases, blowdown effluent and after end use. Heat loss from stack gas, equivalent to 15-20 percent of the fuel energy, usually represents the largest source of inefficiency. Stack gas can be redirected into two types of heat exchangers – economisers, which transfer heat to boiler input water, and pre-heaters, which transfer heat into the boiler input air. Both technologies reduce the required fuel input. Economiser or pre-heater installations can have a simple payback of 1-2 years, depending on the type of boiler.

...a boiler operating at 1035 kPa saturated steam and generating 9100 kg/hr could typically save [up to] 2.4 GJ/hr using an economiser to reduce its flue gas temperature from 288°C to 150°C.

Blowdown effluent volume is usually 4-8 percent of total steam produced but can be as high as 10 percent if input water has a high concentration of solids. Blowdown effluent can be redirected into heat exchangers that transfer the heat to boiler input water.

...if a 1000 kPag [gauge] generates 4550 kg/hr of steam and has a blowdown rate of 10%, the heat recovery potential is ~0.22 gigajoules per hour. At a fuel cost of $4/GJ, and 80% combustion efficiency, an annual saving of about $8400 could be achieved.

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83 For example, four-pass boilers extract more heat from the flue gases before they leave the boiler - they effectively have an economiser built in.

84 Ibid.

85 Ibid.
In some applications, it may be economical to recover heat after end use, whether in steam or some other fluid. End use fluid heat can be redirected into a shell and tube heat recovery unit, which can transfer heat to boiler input water with up to 80-90 percent efficiency. In applications where both high pressure and low pressure steam is required, heat from the high pressure end use may be useful for the low pressure end use.

...high-pressure superheated steam is used to drive a turbine for the generation of electricity, and the turbine exhaust steam is used for heat transfer applications. In these systems the condensate is generally returned to the boiler for re-use, and the overall efficiency is almost 80%.86
Optional Reading


Key Words for Searching Online

Boiler energy efficiency, steam distribution pipes, fire-side fouling, water-side fouling, economiser, heat exchanger.