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A review on boilers energy use, energy savings, and emissions reductions

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ABSTRACT

Boiler is a widely used steam generating system in industries and power plants. A significant portion of the world energy consumption is being used in boilers. A small improvement on the boiler efficiency will help to save a large amount of fossil fuels and to reduce CO_2 emission. This study describes the amount of energy used in boilers, ways employed to evaluate their energy efficiency, losses occurred and their causes, ways of waste heat recovery and minimizing heat loss using technologies, role of maintenance activities, and technical education to make people aware of the energy usage. Latest published literature on the above mentioned topics which includes PhD and MSc theses, journal articles, conference proceedings, reports and web materials have been reviewed and reported. It is found that a substantial amount of energy is wasted through high temperature flue gas or exhaust of the boiler. Also, some other unavoidable losses occurr due to various reasons. However, waste heat could be recovered using different technologies as a useful form of energy such as electricity, heat, refrigeration effect, etc. The efficiency of the boiler can be improved by doing scheduled maintenance work, which helps to run a boiler at its highest efficiency. In order to create awareness about energy use, education programs and seminars need to be arranged on regular basis for the staff involved. This will help them to understand the importance of the energy as being used in the boiler system as well as the impact of their actions during the operation of the boiler.

1. Introduction

Boilers are pressure vessels used for heating water or producing steam to provide heating facility in industries and to generate electricity through driving steam turbines. Boilers are also used for providing space heating for buildings as well as for producing hot water and steam required by users such as laundries and kitchens [1]. Fossil fuels such as coal, gas, oil etc., and nuclear energy, are being used to generate a major portion of world's electricity and generally boilers are the best choice to convert these types of energy into electricity [2,3]. Hence, it is obvious that enhancement of the efficiency of a steam boiler by just a small fraction, will reduce a vast amount of energy consumption in electricity generation. Again, despite the depletion of fossil fuel reserves and environment protection issues, the oil, natural gas and coal demand is expected to rise up to 47.5%, 91.6%, and 94.7%, respectively between 2003 and 2030 [4]. Moreover, most of the industrial heating systems employ boilers to produce hot water or steam. Therefore, an efficient boiler has also a significant influence on heating-related energy savings [5]. A substantial amount of energy can be saved by adopting energy saving measures and by improving the overall boiler efficiency.

In the combustion chamber of a boiler, fossil fuel burnt and the produced heat is transferred through hot flue gas to water. As the hot flue gas transfers heat to water by convection heat transfer, a major portion of heat is lost through the outgoing flue gas. As the temperature of the flue gas leaving a boiler typically ranges from 150 to 250 °C, about 10–30% of the heat energy is lost through the process [6,7]. Other heat losses from a boiler are radiation, blow-down, fly ash and bottom ash losses [8,9]. in order to run a boiler plant at its maximum efficiency, it is necessary to identify the major source of energy wastage

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Nomenclature

AAS	Actual Air supply (kg)
AF	Air fuel ratio (kg/kg)
AC	Alternate Current (A)
C	Carbon
CO	Carbon mono oxide
CO2	Carbon dioxide
C_p	Specific heat of moisture (kJ/kgK)
C_{pg}	Combustion gas specific heat (kJ/kgK)
EA	Excess air
GCV	Gross Calorific Value (kJ/kg)
H	Hydrogen
HHV	Higher heating value (kJ/kg)
K	Constant
LHV	Lower Heating Value (kJ/kg)
L_{stack}	Energy loss through stack
M	Mass of moisture in fuel (kg)
m_a	Mass flow rate of air (kg)
m_f	Mass flow rate of fuel (kg)
m_g	Mass of combustion gas (kg)
N	Nitrogen
O2	Oxygen
ppm	Parts per million
RTD	Resistance Temperature Detector
TDS	Total Dissolved Solids
T_a	Temperature of air (K)
T_C	Combustion Temperature (K)
T_f	Temperature of fuel (K)
T_{stack}	Stack temperature (K)
VFD	Variable Frequency Drive
VSD	Variable Speed drive
η	Efficiency (%)

and recover the energy which is wasted.

The efficiency of boiler is the ratio of the net amount of heat which is being absorbed by the generated steam to the net amount of heat supplied to the boiler. This can also be determined by subtracting the net amount heat lost from the boiler from the net amount of heat supplied to the boiler [10]. Hence to improve the boiler efficiency, the amount of heat being wasted from the boiler needs to be minimized by optimizing some parameters such as excess air, fuel flow rate, steam demand, etc. [11]. To ensure complete combustion, a boiler is to be provided with more combustion air than what is theoretically suggested. Otherwise, there will be a rapid buildup of carbon monoxide in the flue gas, and in extreme cases, smoke will be produced. On the other hand, too much excess air increases the quantity of unnecessary air that is heated and exhausted at the stack temperature [12]. A typical heat balance in a boiler is shown in Fig. 1.

According to Fig. 1, 10–30% of the input heat is wasted through the flue gas and this is the highest source of heat loss in the boiler system. Since most of the heat is being wasted through the high temperature flue gas, the recovery of heat from high temperature exhaust can result in significant energy savings [1,13,14]. Harnessing the waste heat from the high temperature flue gas could be a huge energy savings potential for a boiler system. However, the boiler efficiency can be improved by minimizing this loss supplying optimizing excess air ratio using a VSD (variable speed drive) [15–17]. A VSD is used on the fan motor to change excess air ratio. Fig. 2 shows boiler efficiency with the flue gas temperature reduction.

Fossil fuel consumption is directly related to the emission of CO_2. Environmental protection regulations insist to reduce the emission of CO_2 [19–21] as this is significantly responsible for the greenhouse effect. Hence, to reduce the emission of CO_2 and consumption of fossil fuels, the efficiency of the current energy systems must be improved. There are many ways to reduce energy and heat consumption and carbon dioxide emissions [21–23]. Thermal efficiency of the power plant is around 30.12% for the gross generator output and the maximum energy loss occurs in the boiler. As a result, the performance of the power plant could be greatly improved by improving the performance of the boiler, since this will contribute to the largest improvement to the plant's efficiency [24].

From the literature, there is no comprehensive review on energy use, savings, associated bill savings and avoided emission, along with cost benefit analysis. It is expected that this study will fill that gap. Furthermore, the study could provide important guidelines for future research and development allocations and energy projects to reduce boiler energy use. It will create awareness among the industrial energy users to reduce the boilers energy uses along with environmental pollution reduction.

2. Energy used in boilers

Most of the major industrial processes use steam. USA alone is consuming and burning about 37% of the total fossil fuel to produce steam. This steam has been used in different processes such as heating, concentrating and distilling liquids, drying, etc. Major energy intensive industries allocate significant part of their primary fuel consumption to steam generation: food processing (57%), paper and pulp (81%), petroleum refining (23%), chemicals (42%), and primary metals (10%) [9]. Saidur and Mekhilef [25] reported that 20% of total energy consumption is used in process heating in a rubber producing industries in Malaysia. Fig. 3 shows different types of energy consumption along with process heat in rubber industry in Malaysia. In 2012, U.S. electric utilities converted 38 billion GJ_{en} of coal, natural gas, and nuclear energy into 12.3 billion GJ_{elec} of electricity [26], an average efficiency of 32%. Electricity generation at these plants is performed by combustion fuel (e.g., coal and natural gas) or utilizing nuclear reactions to heat a fluid. The resulting hot fluid drives the blades of a turbine and its associated generator, thereby converting thermal energy into mechanical energy and then electric energy [27–29].

To supply steam for a textile plant significant amount of energy is required. Fig. 4 shows energy consumption for generating steam and other types of final energy consumption in a textile plant in the U.S. The percentages may vary from one country to another, but this figure gives a hint of final energy end-use in the textile industry. In the U.S. textile industry motor-driven systems and steam generation systems have the highest share of the end-use energy use and each accounts for 28% of total final energy use [30].

3. Energy audit for boilers

Energy audit is a systematic approach to investigate industrial

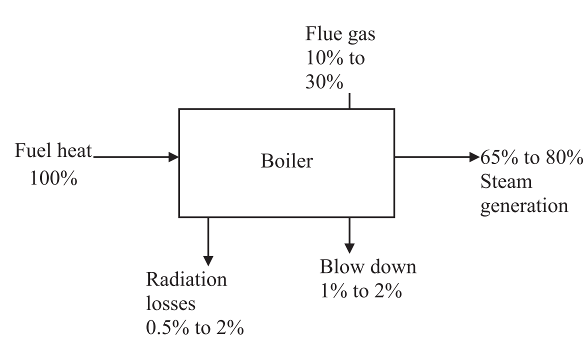

Fig. 1. Typical Heat Balance of a boiler [1].

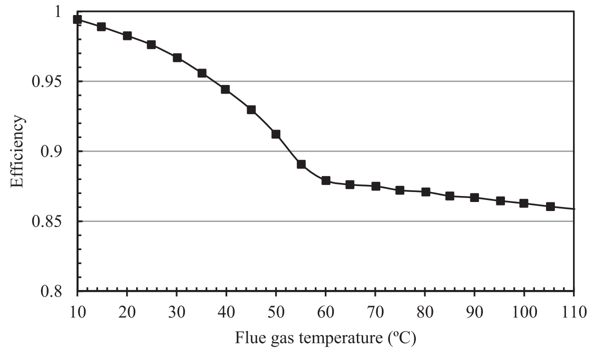

Fig. 2. Efficiency of a boiler with the flue gas temperature reduction [18].

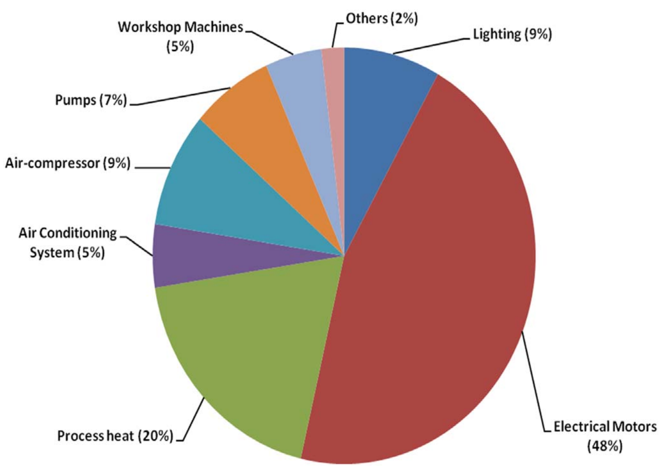

Fig. 3. Energy used by process heat in rubber industries [25].

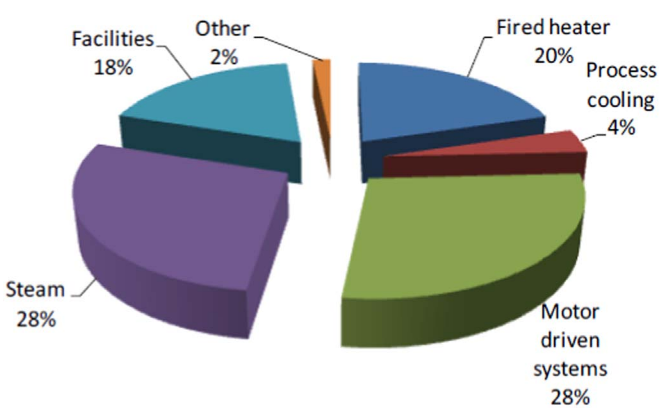

Fig. 4. Final Energy End-Use in the U.S. Textile Industry (U.S. DOE, 2004) [30].

energy consumption and to exactly locate the sources of energy wastage. This is a useful tool for an organization to analyze and understand its energy utilization. It also helps to decide on budgeted energy distribution in different section of an organization, plan energy consumption, which will improve their energy efficiency, curb energy wastage, and, significantly reduce energy costs [31,32]. The energy consumption cost is a major part of a production process cost and often forms a major cost of the plant. The energy audit serves to identify and quantify all the energy consumptions in a facility, in an attempt to balance the total energy input with its use. Thus, energy audit can be used as a systematic method for policy making in the area of energy management. The energy audit study becomes an effective tool in defining and pursuing a comprehensive energy management program. A comprehensive review on types of energy audit, objectives, benefit and energy audit process is outlined by Saidur [31,33].

3.1. Tools for energy audit

Energy audit starts with a walk through visit and meetings with plant officials and interviewing of the site operators. Walk through visit, facility utility bills such as electricity gas and water etc., and other operating data help to become familiar with the building operation and to identify any glaring areas of energy waste or inefficiency. Utility bills for a 12–36 month period are needed to allow the auditor to evaluate the facility's energy demand rate structures and energy usage profiles. But for detailed energy audit, more detailed informations about facility operation are required. To collect information of the boiler operation following tools are needed.

3.1.1. Flow meter

To measure wet, saturated, and superheated steam and water flow accurately.

3.1.2. Exhaust gas analyzer

To measure the efficiency of combustion and the levels of different pollutant gases as accurately as possible at the chimney of the boiler.

3.1.3. Pressure probe

Requirement of pressure in boiler system varies from one place to another to obtain the maximum combustion efficiency. Pressures are measured at various locations of a boiler using pressure probes, which can be used without interfering the normal operation of the boiler.

3.1.4. Clamp-on power meter

To measure power consumption, current consumption, load factor and power factor by different electrically driven system clamp on power meter can be used. The clamp-on feature of the meter enables to record the measurements without disrupting normal operation.

3.1.5. Portable tachometer

Portable tachometer is useful for measuring the speed of any rotating part of the boiler system. Optical type tachometers are preferable due to the ease of measurement.

3.1.6. Thermocouple sensor

Thermometer/thermocouple sensors are used to measure temperature at different location. RTDs and thermistors are most commonly used temperature measuring sensors. To store the data a data logger should be connected to temperature sensors. Thermal image camera or infrared thermometer also can be used to measure the temperature of a place of the system which is not accessible for thermocouple sensors.

3.1.7. Data logger

Different types of parameter of the system are needed to collect for longer periods of time. Data loggers are employed to record data such as temperatures of different location of the boiler, power consumption by motors, flue gas composition for a certain period of time. Measuring tape, slide calipers, etc., are needed to measure the dimensions of boilers and steam pipes as well as other important parameters of the system. Some laboratory instruments are also needed to facilitate the determination of characteristic features of the fuel. Thermogravimetric analysis, ultimate analysis, and heating value determination are commonly used laboratory related work needed in energy audit.

A detailed financial analysis is also needed regarding the implementation cost, operating cost savings, and the amount of investment.

4. Losses in boilers

The thermal efficiency of boilers producing superheated steam or heating thermal oil depends execusively on the amount of heat loss. The ways of heat loss varies depending on the type of fuel, type of boiler, operating conditions, etc. Bujak et al. [34] reported that the heat loss occurs in gaseous and oil fuels fired boilers through chimney, through the external surface of the boiler to the atmosphere, and due to incomplete combustion. Each boiler also loses heat due to technical and operating conditions, which influences heat efficiency. Gupta et al. [35] reported that the sources of heat loss in coal fired boilers are unburnt carbon in refuse, dry flue gas, moisture in fuel, radiation, blow down, and burning of hydrogen. Energy can be lost due to open condensate tank [22,36]. Boilers energy efficiency varies from 20% to 92% depending on the fuel type and purpose of the boiler [24]. Thermal efficiency of coal fired boilers varies between 81% and 85%, for oil between 78% and 81% and for gas between 76% and 81% (HHV). Poor maintenance of boilers can lose up to 30% of the original efficiency [37]. The major portion of heat loss occures due to high air/fuel ratios, steam generation under rated capacity, surface thermal losses, and high flue gas temperatures [38]. Heat losses occur in every section of boiler system. All losses can be categorized into four broad categories.

- Heat carried away by dry flue gasses (Excluding water vapor).
- Heat carried away by hot water vapor, including both sensible and latent heat.
- Heat loss due to unburned carbon in fuel, incomplete combustion, conduction, radiation and convection losses from the outside surface.
- Blow-down loss [39].

4.1. Heat loss due to stack gas

The largest portion of energy loss in a boiler occurs through the stack gas. The temperature and volume of stack gas leaving the boiler are the main factors for the heat loss assessment. Therefore, reduction of any of these parameters will reduce the heat loss. To eliminate stack loss, the temperature of stack gas would have to be reduced to boiler surrounding temperature. But due to the economical infeasibility and limitation in heat transfer principle these losses are unavoidable [8,39]. Excessive flue gas may result from leaks in the boiler, excess air supply due to high frequency of forced draft fan and leaks in the flue gas duct, which is responsible for reduction on heat transfer to the steam and increase in pumping requirements [30,37]. Stack gas heat loss can be minimized by taking following measures:

- Excess air optimization
- Maintaining clean heat transfer area
- Addition of flue gas heat recovery systems

The volume of stack gas is reduced because of less excess air. Thus, the flue gas velocity decreases due to lower volume of stack gas allowing more time for absorbing heat from flue gas and temperature of flue gas would be lowered. In general, the efficiency of boilers varies from 75% to 90%, so ways should be sought to minimize the resulting 10–25% energy losses in boilers [40].

4.2. Conduction and radiation losses

There is a temperature difference between boilers outer surface, auxiliary equipment, and distribution piping of steam and the surrounding areas. Therefore, heat loss occurs by radiation, convection and conduction from the hot surfaces of the boiler systems. The amount of heat lost depends on the temperature of the hot surface, which in turn depends on the insulation (thickness, thermal conductivity, and condition). To minimize that heat loss, hot surfaces should be covered with insulation material having sufficient resistance to heat transfer [35]. Furthermore, the insulation should be of adequate thickness and it should be in good condition. Also, heat loss depends on the area of the hot surface. Since boilers have large surface areas, heat loss from the boiler by radiation can be significant while operating

Table 1
Approximate Radiation and Convection Losses for a 4-Pass Boiler Well Insulated for High Efficiency.

Firing rate (% of load)	981–3433 kW		3924–7848 kW	
	Operating pressure (69 kPa)	Operating pressure (863 kPa)	Operating pressure (69 kPa)	Operating pressure (863 kPa)
25	1.6%	1.9%	1.0%	1.2%
50	0.7%	1.0%	0.5%	0.6%
75	0.5%	0.7%	0.3%	0.4%
100	0.4%	0.5%	0.2%	0.3%

Table 2
Illustration of Radiation Losses for a Typical 1962 kW Boiler.

Boiler loading (%)	Fuel input (W)	Radiation losses (W)	Radiation loss (%)
25	581,500	46,520	8
50	1,163,000	46,520	4
75	1,744,500	46,520	3
100	2,326,000	46,520	2

at low loads. For a typical boiler operating at full load, heat loss due to radiation and convection is about 2% compared to the total loss as shown in.

Table 1. Since the radiative and convective losses remain the same irrespective of boiler loading, the 2% loss at full load can increase to 8% when the boiler is operating at 25% load as illustrated in Table 2 for a typical boiler [1].

4.3. Boiler short cycling losses [41]

Boiler short cycling loss occurs when an oversized boiler is selected for a specific process where the required heating is low and having a plan for expansion of the plant or process that never occurred [42]. It is common in large industries where a single boiler has been used to supply steam to a large number of production lines but only few production lines are in operation. Space heating or HVAC load estimation without considering the other source of heat such as lights, equipment or people and heat loss through building may lead to oversized boiler selection. This oversized boiler satisfies the building heating requirement very quickly and results in boiler short cycling or may continue the steam generation at a low firing rate of the boiler. However, the boiler thermal efficiency decreases when the boiler is operated at the low firing rate or boiler short cycling occurs [43]. This decrease in efficiency results due to the magnification of the fixed losses at the lightly loaded condition of the boiler. At 50% loading condition radiation loss increases to folds of radiation loss at full load condition. An additional heat loss takes place in pre-purge and post purge processes. The fan is used to force air through the boiler to remove combustible gas mixture that may have accumulated. During purging, heat is removed from the boiler as the purged air is heated [44].

To minimize boiler short cycling loss a facility should have multiple small boilers and the total rated capacity of boilers should be able to meet the maximum expected load [44]. Operator can meet varying demand of steam with multiple small boilers without any cost of the boiler efficiency. Multiple small boilers are also very effective where demand of steam largely varies from season to season, and during low demand small boiler can be used to supply steam rather than operating large boilers year-round [41]. An automatic controller for efficiently shifting the load between the boilers is required in the multiple small boiler system. Efficient controlling of multiple boiler and piping helps to avoid low load operation of the boiler, and thus energy can be saved [42]. Measures are taken to operate boilers on the high fire setting have an average payback period of 0.8 years. On the other hand, the installation of smaller boilers to increase the high-fire duty cycle has an average payback time of 1.9 years (U.S. DOE-IAC, 2006) [30].

4.4. Steam leaks

Steam leakage occurs from pipes, flanges, valves, connections, traps, and process equipment. It can be substantial for some steam distribution systems. The amount of steam leaking from various openings depends on the size of the opening and the working pressure [1]. McKay et al. [45] have conducted a survey to locate and measure the losses in a plant and concluded that the major part of the total loss could be attributed to a small number of large steam or condensate leaks. They also found that the malfunctioning of steam traps can pass 25% live steam where the main boiler had an efficiency of 80%.

4.5. Fouling and scaling of boiler heat transfer surfaces

Fouling, scaling, and soot build up on heat transfer surfaces of boilers act as insulators and lead to reduced heat transfer. This results in lower heat transfer to the water in the boiler and higher flue gas temperature. If at the same load conditions and same excess air setting the flue gas temperature increases with time, this is a good indication of increased thermal resistance to heat transfer in the boiler. Typically, 1–1.5 mm soot build up on the fire-side can increase fuel consumption by about 3–8%. Similarly, for the water-side, scale buildup of 1–1.5 mm can result in additional fuel consumption of 4–9% [46]. In another study it is stated that 9.5% reduction in heat transfer can be found due to the 0.03 in. (0.8 mm) of soot layer and in extreme case 69% reduction could result due to the soot layer thickness of 0.18 in. (4.5 mm) [47]. However, scale deposits occurs due to the presence of calcium, magnesium, and silica in most water supplies, which normally react to form a continuous layer of material on the waterside of the boiler heat exchange tubes. Researchers have shown that 0.04 in. (1 mm) of buildup can increase fuel consumption by 2% for water-tube boilers [47] and 5% for fire-tube boilers [48]. Moreover, scaling may result in tube failures. Tests showed that for water-tube boilers 0.04 in. (1 mm) of buildup can increase fuel consumption by 2% (CIPEC, 2001) [30,47]. When this occurs, the boiler heat transfer surface should be cleaned. On the fire-side, surfaces should be cleaned, while on the water side, scaling and fouling should be removed. For boilers using gas and light oil, it is generally sufficient to clean fire-side surfaces once a year. However, for boilers using heavy oil, cleaning may need to be done several times a year. In addition, preventive steps should also be taken. For scaling, as it is caused by inadequate water treatment, steps should be taken to improve water softening and maintaining a lower total dissolved solids (TDS) level. For soot build up, which is normally due to defective burner or insufficient air for combustion, steps should be taken to repair or retune the combustion system [49,50].

4.6. Blowdown energy losses

Water evaporates in the steam drum leaving the solid particles present in the feed water in steam drum. These solid particles form sludge or sediments in the steam drum, which creates a thermal resistance between steam drum surface and water. Dissolved solids also cause foaming and water carryover into the steam. Hence water needed to be drained at a certain time interval, from the bottom part of the steam drum to retain the levels of suspended and total dissolved solids (TDS) within the standard limits. However, blowdown rate depends on the boiler type, operating pressure, water treatment, and quality of makeup water, it could be in the range of 4–10% of boiler feed water flow rate [30,31,51]. Blowdown losses account for about 1–3% of the fuel consumption [49], but this energy loss can be reduced, thus, makeup water and chemical treatment costs can be saved by optimizing blowdown rate [52]. An automatic blowdown-control system could be used to maintain optimum blowdown rates with a simple payback period of 1–3 year [30,48].

4.7. Heat loss due to moisture in the fuel

During combustion the moisture or liquid water present in the fuel takes sensible and latent heats tobecome super heated steam. The superheated steam produced in the combustion chamber is at the added cost of the heat of combustion going to chimney along with flue gas. The amount of heat taken by the moisture is directly proportional to the amount of moisture present in the fuel. The amount of heat loss due to moisture in fuel can be calculated using Eq. (1) [53,54].

$$\text{Percentage of heat loss} = \frac{M \times \{2452.8 + C_p \times (T_f - T_a)\} \times 100}{GCV \;\; of \;\; fuel} \tag{1}$$

4.8. Heat loss due to incomplete combustion

Incomplete combustion of carbon could occur due to shortage of oxygen in the combustion chamber. The product of incomplete combustion is carbon monoxide which results in the liberation of only 52% of the total heat in the fuel. Thus product formed by incomplete combustion could be burned again with further release of energy. The heat loss due to incomplete combustion can be expressed by Eq. (2) given below [53,54].

$$\text{Percentage of heat loss} = \frac{CO\,(ppm) \times 10^{-6} \times m_f \times 23746.8 \times 28 \times 100}{GCV \;\; of \;\; fuel} \tag{2}$$

4.9. Heat loss due to evaporation of water from combustion of hydrogen in fuel

Hydrogen present in the fuel must be burned during combustion, and from water in the combustion product, which takes heat from the combustion of fuel gets evaporated and finally come out to the chimney as a superheated steam. Thus, heat is lost by sensible heating and evaporation of water. Percentage of heat loss by evaporation of water due to the presence of hydrogen in fuel can be calculated using the Eq. (3) below [53,54].

$$\text{Percentage of heat loss} = \frac{9 \times H_2 \times \{245.8 + C_p(T_f - T_a)\} \times 100}{GCV \;\; of \;\; fuel} \tag{3}$$

4.10. Heat loss due to moisture present in air

Atmospheric air contains water vapor as a moisture. After combustion water vapor present in the combustion air becomes superheated steam at the cost of combustion heat. Thus, certain amount of heat is lost due the presence of moisture in air. The percentage of this loss due to moisture present in air can be calculated using Eq. (4) [53,54].

$$\text{Percentage of heat loss} = \frac{AAS \times Humidity \times C_p \times (T_f - T_a) \times 100}{GCV \;\; of \;\; fuel} \tag{4}$$

4.11. Heat loss due to unburnt carbon in bottom and fly ash

The boiler ash studies shows variability in carbon contents that may be a result of variations in retention time in the reactor, incomplete combustion, temperature variations and fluctuations and variations in moisture content. Carbon content of ash is direct loss of useful carbon of fuel, which are expected to be burned in the combustion chamber [35]. Sensible heat loss ocurrs as the hot ash is being removed from the combustion chamber. But due to some difficulties heat loss due to carbon in ash and sensible heat in the fly ash could be ignored during heat loss analysis of the boiler [55].

5. Boiler energy savings measures

Regulagadda et al. [7] studied a coal fired steam turbine power plant to find and locate exergy destruction processes. It was found that, maximum exergy destruction occurs in the boiler in a coal fired steam turbine power plant. Therefore, for improving the performance of the steam turbine power plant, boiler performance should be improved, which results in largest improvement to the plant's efficiency [7]. Some energy saving potentials for the steam distribution systems are shown in Table 3.

5.1. Excess air control

Combustion air is supplied to the combustion chamber of a boiler to burn the supplied fuel. Only oxygen of the supplied air takes part in the combustion process and other parts of air takes sensible heat from combustion, which is going out along with combustion product through chimney as a stack loss. Therefore, the amount of combustion air should be as low as possible to minimize the stack loss. However, due to some limitations only theoretical air cannot ensure complete combustion of fuels. To achieve complete combustion, supplied combustion air should be more than the theoretically required. Otherwise, higher percentage CO in flue gas or unburnt carbon in the ash could be found as result of incomplete combustion of fuel. Therefore, a boiler should be operated with optimum excess air to minimize the dry flue gas loss. For complete combustion, the optimum air flow can be maintained by the employment of one of the following equipments: [1,24,56] (a) inlet damper control, (b) inlet vane control, (c) variable speed control, and (d) measuring system for oxygen content of flue gas [57]. Chien-Li et al. had shown that when the excess air oxygen concentration is reduced from 4% to 3%, the furnace efficiency is raised by 0.6% [58].

Variable speed drive (VSD) is the most efficient control method which provides the power to the fan motor that can overcome the system resistance at a given condition. Currently, it has been used in available modern industrial and commercial boilers. Application of VSD is particularly effective in frequent low load conditions [59]. Table 4 shows the prospective energy savings as a result of speed reductions due to the incorporation of VSDs in boiler fan.

VSD has been used in refrigeration, heating, ventilation and air conditioning of buildings to reduce energy uses [61]. Variable frequency drives (VFDs) are commonly used to vary pump and fan speeds in heating, ventilation and air conditioning of buildings as shown in Fig. 5.

The higher turndown ratio reduces burner starts, saves wear and tear on the burner, provides better load control, reduces refractory wear, reduces purge-air requirements, and provides fuel savings [62].

5.1.1. Estimation of fuel savings associated with boiler fan speed reduction

Burner turndown ratio can be increased using a fan motor speed control and hence fuel can be saved. Electrical energy could be saved using an inverter to control the speed of an AC electric motor. In addition to this controlling the fan motor speed causes restricted excess air ratio and flue gas losses are minimized. Hence, application of VSD increases the boiler efficiency and saves electrical energy. On the other hand, reduced air supply saves fuel, cut emissions and prolongs the life of the boiler plant [12].

Table 4
Potential savings from VSD [60].

Average speed reduction (%)	Potential energy savings (%)
10	22
20	44
20	61
40	73
50	83
60	89

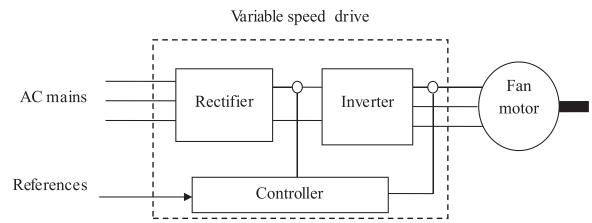

Fig. 5. The block diagram of the variable speed drive system [1,12].

Stack gas loss (L_{stack}) can be expressed as:

$$L_{stack} = \frac{K\,(T_{stack} - T_a)}{CO_2} \quad (5)$$

$$CO_2 = \left[1 - \frac{O_2}{21}\right] \times CO_{2\ max} \quad (6)$$

Value of $(CO_2)_{max}$ is 15.9 and K is 0.53 for petroleum fuels could be found in Ozdemir [12]. Annual fuel saving is calculated using Eq. (7).

$$\text{Fuel Savings } (\%) = \frac{\text{New efficiency} - \text{Old efficiency}}{\text{New efficiency}} \quad (7)$$

$$\eta\,(\%) = (100 - L_{stack}) \quad (8)$$

Tables 5, 6 present the input data needed for boiler flue gas energy analysis.

5.2. Digital control of excess air

The oxygen trim control system will maintain the optimum air fuel ratio, so that the highest possible combustion efficiency could be achieved [39]. The efficiency of the boiler with oxygen concentration in flue gas has been shown in Fig. 6. A digital monitoring control system can be used to achieve best excess air control. This system measures the oxygen and carbon dioxide percentage in exhaust-gas by a probe. According to the measured data, a central digital controller will vary the combustion air flow by controlling inlet damper [63,64].

Based on the measured oxygen percentage in the flue gas, the inlet

Table 3
Energy Efficiency Measures in Industrial Steam Distribution System [37].

Measure	Fuel Saved	Payback Period (Yrs)	Implementation Potential	Other Benefits
Improved insulation	3–13%	1.1	100%	
Improved steam traps	Unknown	Unknown	–	Greater reliability
Steam trap maintenance	10–15%	0.5	50%	
Automatic trap monitoring	5%	1	50%	
Leak repair	3–5%	0.4	12%	Reduce requirement for major repairs
Flash steam recovery/ Condensate return	83%	Unknown	–	Reduce water treatment cost
Condensate return alone	10%	1.1	2%	Reduce water treatment cost

Table 5
Concentration of O_2 and stack gas temperature with and without VSD [12].

	With variable speed drive	Without variable speed drive
Concentration of O_2 (%)	6.9	13.9
Stack gas temperature (°C)	146	195
Ambient temperature (°C)	36	36

Table 6
Input data for boiler energy analysis [12].

	CO_2 (%)	K	Dry flue gas
With variable speed drive	10.6	0.53	5.5
Without variable speed drive	5.38	0.53	16.2

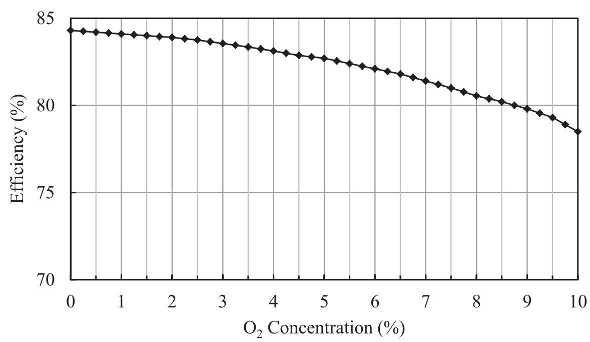

Fig. 6. Combustion efficiency versus oxygen concentration [1].

air damper will be automatically adjusted to attain an optimum excess air set point. To achieve maximum possible combustion efficiency, the required excess air is different for different fuel, as the combustion process of different fuel is not same. Thus for optimizing the combustion efficiency of gas fired boiler, the oxygen concentration set point should be 1.7%, which corresponds to 10% excess air that provides highest combustion efficiency [65,66]. Fig. 7 displays the boiler oxygen trim system fitted on boiler.

To achieve maximum combustion efficiency during boiler operation, percentage of supplied excess air should be 5–10% for natural gas, 5–20% for fuel oil, 15–60% for coal [68]. The variation of combustion efficiency and Stack temperature with different amount of excess air is presented in Table 7 [68,69].

5.3. Improving combustion efficiency

Combustion efficiency is directly related to the liberation of energy content of a fuel through combustion reaction and transfer into usable heat. It can be measured by measuring the exhaust temperature, oxygen or carbon monoxide concentrations in flue gas. Thus, lower combustion efficiency also leads to high emissions of unburnt pollutants such as CO and soot [70]. In ideal case, a precise amount of air is required to completely react with given quantity of fuel. In real combustion, the proper mixing of air and fuel cannot be achieved and "excess" air must be supplied to completely burn the fuel. Lower amounts of supplied air will generate incomplete combustion (carbon monoxide emission) or unburnt carbon in bottom or fly ash. Thus, a portion of heat content of the fuel is being wasted. Due to further reaction of carbon monoxide and unburnt carbon can generate a certain amount of heat. On the other hand, too much excess air increases the stack loss by increasing the flue gas volume and consequently the oxygen concentration in flue gas will increase. Therefore, the amount of excess air should be optimized by analyzing flue gas oxygen or carbon monoxide concentrations [41].

Stoichiometric air is the minimum amount of air that contains required amount of oxygen for complete combustion of a given fuel. The example of the chemical equation for the combustion of natural gas with stoichiometric air is

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \quad (9)$$

From the above example, it is clear that stoichiometric air for different fuel should be different as the chemical formula and constituent chemical elements are not similar. The mass of air required to completely combust one unit mass of a given fuel is known as stoichiometric air fuel ratio. For natural gas, AF_s is about 17.2 kg-air/kg-ng. The quantity of air supplied in excess of stoichiometric air is called excess air, EA. The combustion temperature, T_c, can be calculated from an energy balance on the combustion chamber (Fig. 8), where the chemical energy released during combustion is converted into sensible energy gain of the gasses [67,71,72].

The energy balance equation can be written in terms of inlet air temperature (T_a), LHV, stoichiometric air fuel ratio, excess air (EA), and combustion gas specific heat (C_{pg}) [67].

$$T_c = T_a + LHV/[\{1 + (1 + EA) \times AF_s\} C_{pg}] \quad (10)$$

Combustion efficiency can be primarily identified by measuring the amount of unburned carbon in bottom and fly ash and oxygen in the exhaust. Gaseous and liquid fuels can be burnt using well-designed conventional burners at excess air levels of 15%, but in order to reduce emissions high excess air level of 25% is required. Li et al. had shown that retrofitting a coal fired boiler with louver concentrators and modified seconday air reduces the carbon content in the fly ash greatly from 9.55% to 2.43% [73]. Combustion efficiency is not the same for all fuels. In general, gaseous and liquid fuels burn more efficiently than solid fuels [74].

5.4. Heat recovery from flue gas

Boiler exhaust temperature ranges from 150 to 250 °C [75] due to the limitation in heat transfer area between combustion product and water or steam and condensation of flue gas. Thus, a huge amount of heat energy is lost through boiler exhaust or flue gasses. About 10–20% of input energy may be lost through high temperature flue gas [6]. Therefore, boiler efficiency could be improved by recovering part of the total heat content of flue gas. This heat can be used to preheat combustion air, boiler feed water within the boiler, or as driving heat source for other purposes such as absorption chiller.

5.4.1. Economizer

The common way of recovering heat from the flue gas is preheating of feed water and combustion air using a heat exchanger (commonly called an economizer) installed as shown in Fig. 9. The amount of heat

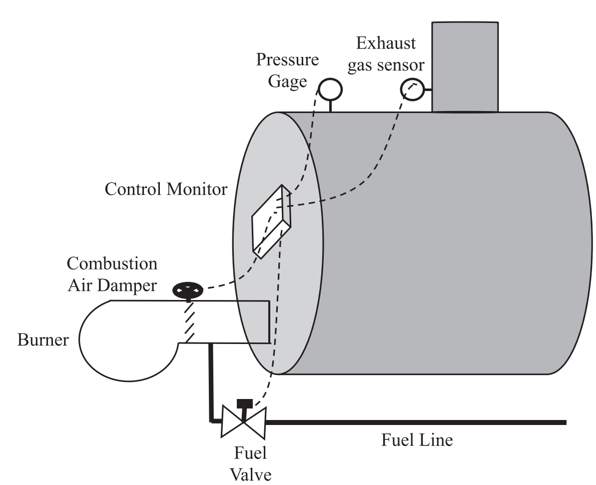

Fig. 7. Oxygen trim system for flue gas recovery [67].

Table 7
Combustion efficiency at different excess air [68].

Combustion Efficiency (%)						
Excess %		Net Stack Temperature (°C)				
Air	Oxygen	93	149	204	260	316
9.5	2.0	85.4	83.1	80.8	78.4	76.0
15	3.0	85.2	82.8	80.4	77.9	75.4
28.1	5.0	84.7	82.1	79.5	76.7	74.0
44.9	7.0	84.1	81.2	78.2	75.2	72.1
81.6	10.0	82.8	79.3	75.6	71.9	68.2

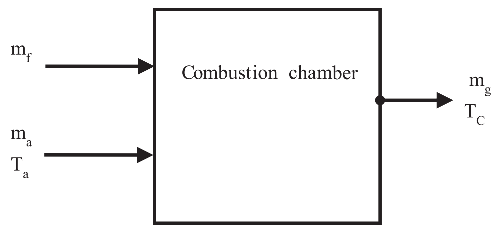

Fig. 8. Energy balance for combustion chamber.

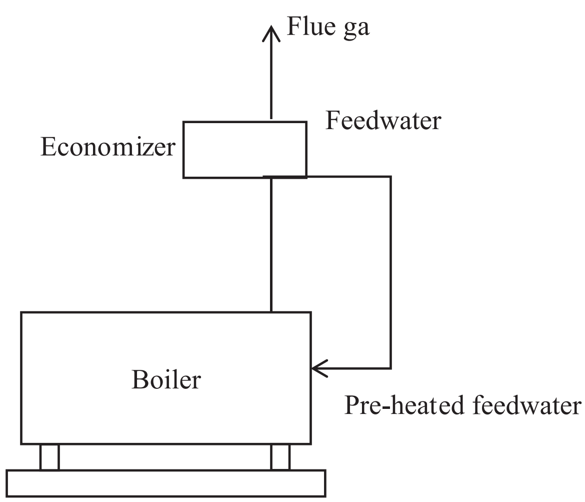

Fig. 9. Arrangement of a typical economizer.

recovered depends on the temperatures of flue gas and fluid to be heated. But the major problem associated with flue gas heat recovery is corrosion due to acid condensation [9,76]. The sulfur in the fuel combines with oxygen during combustion to form sulfur dioxide, which combines with steam resulting sulfuric acid in the flue gas. Steam is formed by the oxidation of hydrogen and moisture present in the fuel. Thus, acid condensation takes place when the flue gas is cooled below its acid dew point [77].

Therefore, to prevent acid condensation the flue gas temperature could be minimized to a certain temperature which is well above the acid dew point temperature. Otherwise, heat recovery system should be designed to withstand acid corrosion. The amount of acid content in flue gas is directly related to sulfur content of the fuel. Therefore, allowable minimum exhaust temperature also depends on the fuel used in boiler. Some allowable exit stack temperature are given in Table 8 [1].

5.5. Preheating combustion air

Combustion air preheating is the most potent way to enhance the boiler efficiency and steam generation [78–80]. High temperature exhaust gas stream can be used as the source of the heat energy and a heat exchanger can be used to transfer the heat energy to the incoming combustion air [81,82]. Thus combustion air gains a large portion of sensible heat that is required to take part in the combustion process. Fuel savings for different flue gas temperature and resulted preheated combustion air temperatures are shown in the Table 9 below [83].

5.6. Condensate recovery

In most steam systems, steam is used for process heating by extracting its latent heat. The resulting condensate is at steam temperature and still contains a considerable amount of energy. For example, if steam is used at 690 kPa, then the condensate contains about 25% of the heat used to produce steam and will be lost if the condensate is not returned to the system [84–88]. Therefore, returning condensate to the boiler feed water tank will result in significant fuel energy savings. Since, condensate is the distilled water which is ideal for use as boiler feed water. Therefore, condensate recovery helps to reduce water consumption (water cost), water treatment cost, and blow down [1,89]. A piping network is needed to be employed for recovering condensate from different heating facilities, which involves a financial investment. But, the substantial savings in energy and chemicals costs makes building a return piping system attractive. It has been found that 2% of the boiler population can achieve a 10% energy savings with a payback period of 1.1 years [9,90,91].

5.7. Steam traps

Steam traps are used in steam systems to remove condensate and non-condensable gases. They are mainly used in buildings for steam heating coils and for condensate removal from steam headers, as shown in Fig. 10. There are many types of steam traps as shown in Fig. 11. The operation of steam traps is important because if they fail to operate properly and allow live steam to pass through them from the steam side to the condensate side, it results in obvious loss of energy [92]. In addition, if the traps are unable to remove air at start-up times or if they are unable to remove condensate at a sufficient rate, the resulting reduced capacity and longer periods to heat up would also result in energy wastage. Water hammering can eventually result in damage to valves and other components in steam systems, which could result in steam leaks [1,93,94]. By ensuring the proper operation of steam traps, significant amounts of energy can be saved. Steam traps are needed to be monitored regularly, which can prevent the malfunctioning of 15–20% of the traps. A regular system of steam trap with regular checking program and follow-up maintenance is also able to save energy up to 10% [91,95,96] and the payback period is 0.5 years [90]. Though the payback period is very short, this is not implemented in every steam system because some steam plant management separately budget their maintenance and energy costs. Addition of automated monitors and maintenance program can save even more energy, without significant extra cost. This system will improve the maintenance program, because automated monitoring can give quicker response if a steam trap fail or malfunction. Using automatic monitoring is estimated to save an additional 5% over steam trap maintenance, with a payback of 1 year [95,97].

Table 8
Acid Dew point for Common Fuel Types [1].

Fuel	Acid dew point temperature (°C)	Allowable exit stack temperature (°C)
Natural gas	66	120
Light oil	82	135
Low sulfur oil	93	150
High sulfur oil	110	160

Table 9
Percent Fuel Savings Gained from Using Preheated Combustion Air [83].

Furnace Exhaust Temperature, °C	Preheated Air Temperature °C/ Percent of fuel savings					
	316	427	538	649	760	871
538	13	18	–	–	–	–
649	14	19	23	–	–	–
760	15	20	24	28	–	–
871	17	22	26	30	34	–
982	18	24	28	33	37	40
1093	20	26	31	35	39	43
1204	23	29	34	39	43	47
1316	26	32	38	43	47	51

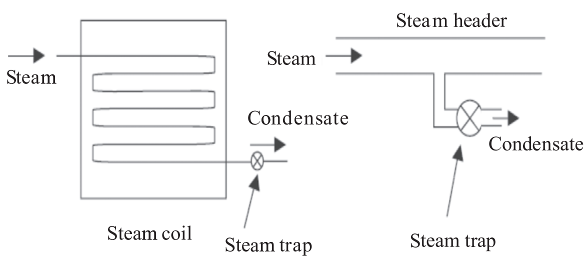

Fig. 10. Application of steam traps [1].

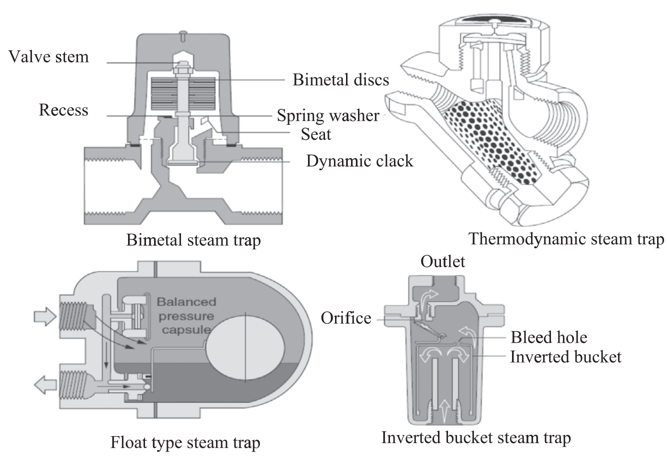

Fig. 11. Common types of steam traps [1].

5.8. Heat recovery technology

From economical point of view the equipment which needs minimum capital outlay are preferable for recovering waste heat and to transfer to a suitable heat sink. Harnessing the waste sources within the system is also preferable from which it is being emitted [98]. Preheating combustion air and boiler feed water are the first choice to utilize the recovered heat from boiler exhaust. Some other solution requires higher investment such as heat pumps to provide a temperature lift [99,100], Organic Rankin Cycle or Kalina Cycle to generate electricity [101–103], absorption refrigeration cycle for providing air conditioning or cooling effect [104–106]. Heating requirement outside the boundaries of the boiler plant is also an option for a third party to harness the waste heat source but these options also require higher capital investment and long payback period [107]. However, initial technology selection criteria are based on the temperature and flow rate of boiler exhaust. Required temperature and flow rate of exhaust varies for the equipments which are expected to run by the exhaust. Some parameter of boiler exhaust (dust, sticky) also influences the technology selection process. Efficiency of heat recovery and ease of installation, project payback period also have the significant influence on technology selection [107–109].

5.8.1. Heat exchanger technology

There are two types of heat exchangers, Gas-gas heat exchanger and Gas-liquid heat exchanger that can be used to recover waste heat from boiler exhaust [107,110–112]. The most common use of Gas-gas heat exchanger is preheating combustion air by passing the boiler exhaust and fresh air in different flow configuration between plates or tubes through which heat is transferred [113]. This heat exchanger also can be used for heating any gaseous substance or fresh air to fulfill a process requirement. Rotating regenerators or heat wheels and plate heat exchanger are the generally used gas-gas heat exchanger [114]. Gas-liquid heat exchanger is also commonly used heat exchanger in the steam generation system. Generally, it is used for heating boiler feed water using boiler exhaust. It is known as economizer which widely exists in both industrial and domestic applications [115–117].

5.8.2. Heat pump systems

Heat pumps are able to create a temperature lift of a heat source which makes the heat source useable at higher temperature and in case of waste heat recovery from low temperature exhaust; this technology can lift the temperature for using the recovered heat at higher temperature [118]. It is potential to create temperature lift of boiler exhaust economically in excess of 40 °C, but the overall efficiency is reduced due to energy requirement of the heat pump [107]. Application of heat pump is common all over Europe but fewer in UK. A survey regarding public attitude on waste heat recovery [119,120] revealed a major portion of the food industry in UK considers heat pumps as a 'risky' or 'unsure' even though the payback period varies from 2 to 5 years [99,100,121] in some case studies in UK. UK government has been emphasizing on heat pump application through latest schemes to encourage the utilization of this technology [107,122].

5.8.3. Electricity generation

5.8.3.1. Thermoelectric units. Thermoelectric module works on the temperature differential and produces electric current at the electric terminals [123–125]. The module is a collection of p-n couples which are thermally in parallel and electrically in series. According to the provided data by manufacturer Hi-Z [126,127], a thermoelectric module can generate electric power in the range of 20–50 W for a temperature difference of around 200 °C. Thus large number of modules in series can be configured to increase the amount of generated power [128,129]. Since the energy conversion efficiency and electrical output of the modules is extremely low, if there is a requirement for a low electrical power near the heat source, thermoelectric modules could be used by utilizing waste heat source. Thermoelectric modules may not be the most desirable due to low energy conversion efficiency, but as a potential option it could be investigated for individual cases [107,130].

5.8.3.2. Rankine cycle. A heat source is needed to vaporize a working fluid which in turn would drive a turbine. The turbine is connected to the electric generator which will generate electricity. The working fluid would then be condensed and returned to the heat source. As the traditional Rankine cycle is not suitable for heat sources below around 240 °C, the organic Rankine cycle (ORC) with organic working fluids could be used for electricity generation by recovering waste heat from boiler exhaust. It has been reported that organic Rankine cycle could be suitable for electricity generation using sources as low as 40 °C [131]. DRD Power [132] have been demonstrated a 200 kW unit using low pressure steam, which is installed in a chemical factory with joint funding of Carbon Trust and a number of sources [133]. But Organic Rankine cycle offer efficiency (up to 18% [103]) and the capital costs are high. It could be preferable if government aid on funding is available for such a project, thus the payback period could be considerably decreased [134,135].

5.8.3.3. Kalina cycle. An updated and customized version of Organic Rankine cycle known as Kalina cycle, which can be used for exploiting the waste heat sources. Ammonia-water mixture is the working fluid of the Kalina cycle and as the boiling of mixture occurs over a wide range of temperatures which enables the Kalian cycle to recover heat from the boiler exhaust until the exhaust temperature is reached to a lower limit [51]. This system needs to use a lower pressure heat exchanger and allows varying the concentration of ammonia in water at the condenser according to the temperature of heat source [51]. Researchers have shown that the Kalina cycle with novel features is capable to increase the output power of up to 20% compared to ORC [136]. However, a study found that this improvement may be as small as 3% [137], which may not be enough to cover the higher maintenance costs and higher investment [138,139]. Currently, it can be found in low-grade waste heat recovery and geothermal power plants [140]. This cycle is a potential choice to recover waste heat from boiler exhaust and generate electricity. But it still needs further demonstration to confirm the projects justifiability.

5.8.3.4. Micro co-generation. In order to comply with the Kyoto commitment, Japan was required to reduce its greenhouse gas (GHG) emissions by 14% on average during the period between 2008 and 2012 [141,142]. Furthermore, in order to realize a sustainable low-carbon society, Japan has announced drastic goals to curb the emissions of GHG, with 2050 as the target year, as well as scenarios for achieving the goal. However, Japan had increased total GHG emissions by 12.2% in 2007, among which, the residential sector added the GHG emission by 10.8% [143]. Cogeneration has been considered worldwide as the major alternative to traditional systems in terms of significant energy saving and environmental conservation as well as GHG emission [144,145]. Heat should be produced in combination with power, as this increases energy efficiency significantly which is an extremely important to energy sustainability [146]. The most promising target in the application of CHP lies in energy production for buildings, where small-scale and microscale CHP is usually installed [147]. Small-scale and micro-scale CHP systems can help to meet a number of energy and social policy aims, including the reduction in greenhouse gas emissions, improved energy security, investment saving resulted from the omission of the electricity transmission and distribution network, and the potentially reduced energy cost to consumers [148]. Currently, micro-scale and small-scale CHP systems are undergoing rapid development, and are emerging on the market with promising prospects for the near future [147,148]. Combination of cogeneration technologies to various thermally fed systems such as absorption or engine-driven chillers [149–153] allow for setting up a so-called trigeneration system. In addition, high-efficiency electro-energetic technologies such as electric heat pumps [150,152] well fit into the existing energy systems to enhance the overall performance. Bernotat and Sandberg [146,154] reported on the possibilities of using CHP for clustered dwellings in Sweden and the Baltic states, concluding that small scale CHP has high perspectives if the total heat demand in an area is high enough. Dentice d'Accacia et al. [145] reported on the possibilities of residential micro-CHP systems. They present a general survey of market and technological perspective. A demonstration project was reported with a fuel cell in Ref. [155]. The experiments were aimed at assessing the suitability of this kind of system to supply Italian residential customers. Voorspools and D'haeseleer [156] analysed the response of a gas engine cogeneration unit in a house to a certain heat demand. It was shown that an engine is rather slow in response for heating, whereas the electric transient is negligible.

5.8.4. Absorption refrigeration systems

To run absorption refrigeration cycle a heat source is needed instead of a compressor. The working fluid is vaporized upon heating at generator by a low temperature waste heat source (boiler exhaust) and then condensed at the condenser. This condensed fluid flows through an expansion valve to the evaporator, where it is expected to gain latent heat and make the refrigeration effect [106]. Commercially available systems are mainly based on lithium bromide/water and ammonia/water solution. These systems can achieve cooling temperature as low as 7 °C using a waste heat source such as low temperature exhaust [104]. To install an 800 kW sized unit, the overall investment is expected to be around £150,000 (excluding pumps and pipework [104]). Commercial exhaust driven absorption chiller with various capacity can be found in [105,157]. This type of refrigeration systems may preferable in plants requiring which have low grade waste heat source and also need a lot of refrigeration effect within their plant [158]. However, payback periods for introducing absorption refrigeration system in an existing boiler could be around 10 years but, for a new build plant it becomes around 3 years [104].

6. Role of maintenance on boiler energy savings

Systematic boiler maintenance can evade unanticipated failure and minimizes unexpected boiler downtime and energy consumption [159]. Maintenance task should be performed for daily, weekly, monthly and annually basis. A written record should be kept for all performed maintenance work [160]. To ensure the scheduled maintenance work, checklists could be used which will records of executed works and are a way to communicate the boilers' status [161]. All checklists and other record documents should be systematically filed for reference [45,162].

6.1. Keep the boiler clean

Fouling on fire and water side of the boiler tubes is a very common problem of the steam generation system. In fire side of the tubes accumulation of deposits occurs from burning fuel, and the growth of the deposits depends on the types of fuel. Solid fuels tend to foul much more than liquid and gaseous-fueled boilers [47,48,69,163]. Similarly, heavy oil fired boilers face greater fouling problems whereas natural gas fired boilers face a comparatively very low fouling [164,165]. The most likely causes of fouling are low air-to fuel ratios, improper fuel preparation or malfunctioning burner. Dissolved minerals in water forms deposits or scale on waterside of the boiler tubes. Waterside deposit/scale inhibits the heat transfer from tube wall to water which in turn raises the tube wall and flue gas temperatures. An automatic sensor could be used to measure the scale buildup in the running boiler and can be treated chemically [166]. Boiler feed water should be tested daily in small low-pressure boilers and hourly in large high pressure boilers [167]. Large boilers are often equipped with soot blowers to facilitate cleaning the fireside tube surfaces. Regular inspection and cleaning is suggested for small boilers [4168].

6.2. Improve boiler insulation

A simple and economical way of reducing heat loss through radiation and convection is by adding insulation directly to the outer walls of the boiler as well as steam pipes. New materials such as ceramics, fibers which are having a lower heat capacity should be used for insulation. According to the rule of thumb, any surface above 50 °C should be insulated, including steam and condensate piping, boiler surfaces, valves and fittings. Damaged or worn out insulations should be changed and hot spots on boiler casing should be checked and fixed. Outer skin temperature should not be more than 50 °C [169].

Researchers have shown that the improved insulation can save 6–26% [170,171]. Moreover, removed insulation during repairing on steam systems should be reinstalled. Brittle and rotten insulation should be found out by doing regular inspection and replacing with new insulation material can save energy [171].

6.3. Minimize wasted blowdown water

Blown down is the periodical hot water discharge from the bottom of the steam drum to prevent scale formation on boiler tubes. Energy gained by the hot water is being wasted due to this blowdown process and more frequent blowdown intensify this energy loss. Automatic blowdown controls can be used to maintain premeditated boiler water conductivity, TDS, silica, chlorides, alkalinity and acidity to minimize energy through blowdown water [51,172]. For further energy savings, boiler feed water can be preheated by recovering waste heat from blowdown water and approximately 1% improvement on system's efficiency could be achieved [5,173,174].

6.4. Maintenance activities

To confirm cleaned boilers for allowing maximum heat transfer and proper functioning of the safety devices, water supply system, fuel supply systems, electrical components and systems, etc. a scheduled maintenance is necessary [175]. Some other activities are also needed to be done to ensure the boiler operation at high efficiency such as periodical combustion test using flue-gas analysis [22]. Boiler maintenance works can be listed as follows.

- Proper functioning of shut off valves without any water leakage is needed to be ensured.
- Broken pieces or cracks in the refractory walls or layers should be repaired.
- Proper functioning of controls, safety devices, and indicators, including the low-water cutoff devices and regulators, pressure gauge, safety valves, and the pressure release valve should be ensured in the maintenance period.
- Fuel feed system and burners, particularly if your boilers use liquid fuels should be checked carefully. Not doing so will result in inefficient combustion and heat transfer, resulting in higher fuel costs and less effective heating.
- Be sure to clean boiler heat transfer surfaces regularly to remove buildup of soot. Soot can act as an insulator which cuts down on the efficiency of the heat transfer between combustion gas and steam generation [176].

7. Information, education and awareness

Education as a body of knowledge shows indispensable and necessary tools to create awareness and change attitude and values of individuals. Through education people became aware of the citizenship problems, the rational use of energy, and consequently mitigating the presence of barriers, mainly the behavioral ones [177–179]. People think about energy as a commodity and became aware of the fuel price, a social necessity or an ecological resource [179–181]. Table 10 shows energy savings in Brazil using educational program.

Publications and seminars are the main tools for disseminating energy related information. Publications should be targeted audience oriented and technically sound. Hence, several types of publications with appropriate information should be available for different groups of people from maintenance staff to accountants. Another successful way of spreading information is through seminars. They should avoid being too general on one hand and too academic on the other. In order to present interesting case stories in publications and seminars, it is a good approach to set up pilot projects that deal with specific problems. An energy guide label with details of energy savings feature in many countries found to be effective to raise the awareness among the users. Mass media can play an important role by disseminating useful energy savings information to the users so that users may follow energy efficient rules while they use equipment/machineries [33,182–184]. A well-planned employee energy awareness campaign provides a platform to engage and educate [22,185] the workforce by.

- Building a greater understanding of the importance of energy efficiency.
- Creating a sense of ownership for energy management plan.
- Focusing attention on the key issues of importance to an organization.
- Demonstrating how individuals can help to achieve organizational goals.

8. Conclusions

Boilers are commonly used as steam generation systems in different industries for the heating processes. Thermal power plants use boilers to generate steam for steam turbines. A significant portion of the world energy consumption is found to be used for operating boilers around the world to facilitate the heating process or power generation. However, the typical boiler efficiency is in the range of 75–90% and the remaining part of the energy is lost as different forms of wasted heat. To evaluate the efficiency of the boiler and the amount of heat that is wasted from the boiler, energy audit can be performed. This helps to quantify the amount of heat lost through different sources and identify the potential source of waste heat. The efficiency of the boiler can be improved by taking measures to control the potential of waste heat sources.

Heat loss from the boiler occurs in several ways, and stack gas loss is the major source of heat loss among other sources of heat loss. Due to the limitation of acid dew point of stack gas this loss cannot be eliminated, but could be minimized by recoverying waste heat from the boiler exhaust and utilizing the recovered waste heat within the boiler system. Other sources of heat loss such as boiler short cycling and blowdown occurs due to removing of hot water from the steam drum to run the boiler efficiently. However, excessive short cycling and blowdown causes higher heat loss as the hot water is being drained from the steam drum. Some losses occur due to fuel and combustion air quality, such as moisture in fuel and moisture in air. This moisture consumes heat to evaporate and mix with the exhaust gas. Heat loss due to the conduction and radiation occures from the uninsulated surface of the boiler, fouling, and scaling which hinders heat transfer from high temperature combustion product to the water, due to incomplete combustion, energy content of the fuel could not be liberated. Causes, effects, and proposed remedies for the sources of heat loss are reviewed from literature in this study.

Energy saving measures for boiler have also been reviewed and discussed in detail in this study. Different types of energy saving techniques such as excess air control, improving combustion efficiency, utilization of waste heat content of flue gas, and condensate recovery, etc., have been reviewed. An optimized excess air could be maintained using variable speed driven ID fan. VSD operated ID fan consumes less amount of electrical power as well as optimized excess air will reduce stack gas loss by reducing the amount of stack gas. Combustion

Table 10
Energy savings with educational program [177].

Energy saved		Avoided demand-peak		Investments		Cost (US $/kWh)
GWh/yr)	%	MW/yr	%	US$x10^3	%	
69.71	9.2	7.55	3	744.86	0.7	0.010

efficiency can be improved using well designed nozzle or combustion process with minimum use of excess air. By using proper functioning of steam trap and recovering condensate, a significant amount of energy can be saved. Finally, heat recovery technologies can be used to recover waste heat from boiler exhaust and exploit that recovered heat to generate electricity or refrigeration effect. Recovered heat also can be used to preheat combustion air or feed water within the system. Proper maintenance of boiler also helps to save energy and to run the boiler at its maximum efficiency. In order to maximize the heat transfer from flue gas to water and minimize the heat loss in other parts of the boiler, cleaning of heat transfer surfaces on both water and fire side must be conducted. Proper functioning of other equipments need to be confirmed during maintenance work. Moreover, attitude and values of individuals towards energy use needed to be improved through continuous dissemination of knowledge by education, awairness, seminars, or conferences among the technical staff.

9. Recommendations for future work

This study focused on the energy consumption by the boiler for generating steam in different purposes, causes of heat loss and energy saving opportunities in the steam generation system. To estimate the amount of heat lost from a boiler or the operating efficiency of the boiler, energy audit could be done. Hence, the procedure to carryout an energy audit in the steam generation plant has been included in this study. However, most of the boilers have been operated without having periodical energy audit. Though the energy loss through different parts of a new boiler is within the tolerable limit, but energy loss is supposed to be increased with increasing oprating period of the boiler. Thus, energy flow of the boiler needs to be audited at specific time intervals, which helps to identify the sources of major energy loss. The major energy loss occurs due to different causes and can be minimized by taking different remedial actions or using techonologies. Retrofitting of these technologies is needed to be examined experimentally and further technological improvement of them may encourage the end user. Moreover, boiler operation staff as well as other non-technical staff needs to be properly educated and aware about fuel price and impact of fuel consumption.

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