Energy Efficiency and Environmental Impact Assessment of Steam Power Plant Boiler

Ibrahim Hassan M. Sadeek*, Osman Omran Osman, Mahmoud Nady Abdelmoez, Ahmed Hamza H. Ali

Department of Mechanical Power Engineering, Faculty of Engineering, Assiut University, Assiut 71111, Egypt

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Abstract
Energy efficiency optimizes energy use in a specific product, process, or consumption without compromising output or comfort levels. As an integral component of energy conservation policies, it aims to reduce energy intensity, preserve resources, and mitigate environmental impact by reducing CO_2 emissions, optimizing energy use, and minimizing waste. In industrial processes, energy losses occur in exhaust gases or effluents released at various temperature levels. Despite ongoing efforts to mitigate these losses, economic considerations frequently constrain such endeavors. However, adopting various waste heat recovery technologies, like steam generators, is an avenue for capturing and reutilizing lost energy, particularly associated with exhaust gases. This can be done through an energy audit methodology to identify inefficiencies and recommend appropriate waste heat recovery technologies to optimize boiler performance and environmental outcomes. This study aims to present the state of the performance of the steam generator in thermal power plants to enhance energy efficiency. Explore various sources of heat loss and inefficiencies within boiler systems, examining the percentage contributions of different heat loss mechanisms using energy auditing methods.

1. Introduction

Energy efficiency is gaining significant global attention from policymakers. Its central role in bolstering energy security, ensuring affordability, and hastening the transition to cleaner and sustainable energy sources is being widely recognized. International initiatives, particularly those at COP28, are poised to play a pivotal role in shaping the trajectory of future energy efficiency and demand pathways by achieving the ambitious goal of doubling efficiency progress from the 2022 level of 2% to 4% annually until 2030, which could cut today's energy bills in advanced countries by one-third and make up 50% of carbon dioxide CO_2 reductions by 2030 [1]. The World Energy Outlook 2023 emphasized that improving boiler efficiency in steam power plants can substantially reduce fuel consumption and greenhouse gas emissions. Enhancing boiler systems' efficiency is projected to contribute to global energy savings of up to 20% by 2030, underscoring the importance of continuous technological advancements and policy support in the energy sector [2]. Steam plays a pivotal role in influencing both energy efficiency and environmental impact.

*Correspondence author email: Ibrahim_hassan@aun.edu.eg

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Abbreviations		TDS	Total dissolved solids
AAS	Actual Air supply (kg)	T_a	Temperature of air (K)
bcm	billion cubic meters	T_f	Temperature of flue gases at the stack exit (K)
CO	Carbon mono oxide	T_{fw}	The feedwater temperature (K)
CO_2	Carbon dioxide	T_s	The saturated steam temperature (K)
COP28	Conference of the Parties 28	**Symbols**	
EA	Energy Audit	m_f	Mass flow rate of fuel (kg)
GCV	Gross Calorific Value (kJ/kg)	C_{pg}	Specific heat capacity of gases (kJ/kg K)
GW_{el}	Giga Watt Electricity	C_p	Specific heat capacity of steam (kJ/kg K)
IAEA	International Atomic Energy Agency	M	A mass flow rate of the flue gases (kg/s)
IEA	International Energy Agency	$\dot{m}_{fule}$	Mass fuel consumption rate (Kg/sec)
MW	Megawatt	$\dot{m}_{steam}$	A mass flow rate of steam (Kg/sec)
ppm	Parts per million	m	Mass of dry flue gas in kg/kg of fuel

Consequently, it is imperative to attain the highest levels of efficiency in converting thermal energy using more energy-efficient steam generators. Boilers, classified as closed-pressure vessels, play a crucial role in various applications. They are employed for heating water, producing steam for industrial heating, and generating electricity by driving steam turbines [3]. In the boiler combustion chamber, fossil fuel burns and produces heat transferred through hot flue gas to water. As the hot flue gas transfers heat to water by convection heat transfer, a significant portion of heat is lost through the outgoing flue gas. Other losses from a boiler are radiation, fly ash, and blowdown losses. Fig. 1 shows heat balance in a steam power plant boiler [4]. The efficiency of a boiler is the ratio of the net heat absorbed by the generated steam to the net heat supplied to the boiler, and it can be determined by subtracting the net heat lost from the boiler from the net heat supplied to the boiler [5]. During 2021, Egypt had approximately 58.818 GW_{el} (Giga Watt Electricity) of installed electric capacities, and the distribution of installed capacities by source is roughly 90.1% from thermal sources of the total, as shown in Fig. 2 [6]. Electricity generation in these plants involves the combustion of fuel (such as coal and natural gas) or nuclear reactions to heat a fluid. Egypt consumed about 16% of oil and 60% of natural gas in power generation through 2022. Fig. 3 shows the domestic consumption of steam power plants by natural gas in Egypt [7]. Erbas [8] evaluated the performance test for steam generator efficiency, which was determined using direct and indirect methods. In addition, it accounted for environmental aspects by examining flue gas emissions and assessing thermal losses within the system. Chen et al. [9] demonstrated that supply-air humidification enhances overall boiler efficiency with maximum efficiency improvements of 3.7% and 3.8% at excess-air ratios of 1.3 and 1.1, respectively. Additionally, supply-air humidification effectively reduced NO_x concentrations to within emission limits.

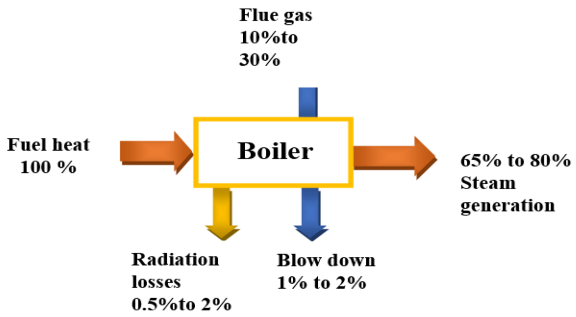

Fig. 1 Heat balance of a boiler [5]

Table 1 A summary of the research performed on the energy audit assessment of steam boilers

Study	Capacity (MW)	Energy Audit	Brief Title	Major Findings	Remarks
Liu et al. (2020) [1]	240	✓	Combustion Adjustment in CFB Boilers	Improved efficiency by adjusting combustion parameters reduced NOx emissions.	Further study is needed on controlling fuel temperature and cost-effectiveness.
Erbas (2021) [8]	-	✓	Thermal Performance in Coal-Fired Boilers	Identified thermal losses and improved efficiency with heat recovery systems	Needs specific studies on economic feasibility and long-term sustainability
Wang et al. (2021) [10]	300	✕	Efficiency Analysis in Pulverized Coal Boilers	Enhanced efficiency with heat recovery systems, reduced emissions	Requires detailed cost-effectiveness and long-term sustainability analysis
Chen et al. (2020) [9]	-	✕	Supply-Air Humidification in Gas Boilers	Improved efficiency by 3.8% with supply-air humidification reduced NOx emissions.	Needs impact analysis on different boiler types and long-term maintenance costs
Sun, Y., Zhang, Y., & Jiang, Z. (2023) [12]	350	✓	Air Distribution Strategies for Supercritical Boilers	Improved combustion efficiency and reduced emissions using CFD for optimal air distribution modes	Detailed long-term sustainability and cost analysis required
Khalid et al. (2020) [13]	-	✓	Intelligent Steam Power Plant Boiler Waterwall Tube Leakage Detection via Machine Learning-Based Optimal Sensor Selection	Used machine learning for optimal sensor selection, improving leakage detection in boilers	Further validation is needed with real-world data.

Dwivedi et al. (2021) [14]	500	✓	Improvement in Energy Efficiency & Heat Loss Minimization during Boiler Operation: A Case Study	Improved energy efficiency and minimized heat loss during boiler operation	Further validation with real-world data is needed

C. Wang et al. [10] Co-firing sludge with coal in power plant boilers is profitable from an economic and environmental perspective, with the best choice being sludge with a moisture content of 80 and a mixing ratio of 30, as it emits the least NOx. Table 1 Summary of the research performed on steam power plant boiler.

This paper reports on the state-of-the-art performance of steam generators, mainly focusing on boilers in power plants. According to the latest literature from six years ago, the enhancement of steam boilers by controlling supply air and combustion efficiency or using machine learning and AI tools effectively improved energy efficiency and reduced carbon emission. The study will explore various sources of heat loss and inefficiencies within boiler systems, examining the percentage contributions of different heat loss mechanisms, such as flue gas loss, radiation loss, blowdown loss, and moisture in the fuel, using energy auditing methods and suggest other ways to improve energy efficiency by optimizing parameters like boiler feed water quality, burner management, and fuel quality on the tube life involves exploring advanced materials for enhanced impurity, scales, sludges, and salt removal in boiler water before use in a steam power plant boiler.

2. Classification of boilers

Steam boilers can be classified on eight bases, as shown in Fig. 4. Based on the tube content boiler, all boilers can be classified as water tubes, fire tubes, and tubeless boilers. The oxidation reaction or combustion occurs inside the boiler to generate hot combustion product gases as input heat for all the existing boilers. The energy in these high enthalpy gases must be transferred from the combusted gas to the water to convert it into saturated or superheated steam. This energy transfer primarily occurs through conduction and convection heat transfers across the boiler walls or surfaces. The hot fluids (combustion gases and water vapor) are directed through the boiler in single- or multi-pass configurations to achieve sufficient heat transfer area .

Furthermore, the efficiency of existing boilers is influenced by heat transfer ability and various losses, particularly flue gas loss. Improving boiler efficiency involves designing the characteristics and materials of boiler components to enhance heat transfer ability, promote complete combustion, and minimize emissions and losses. Literature indicates that the most significant loss in boilers is attributed to high-temperature flue gas [15].

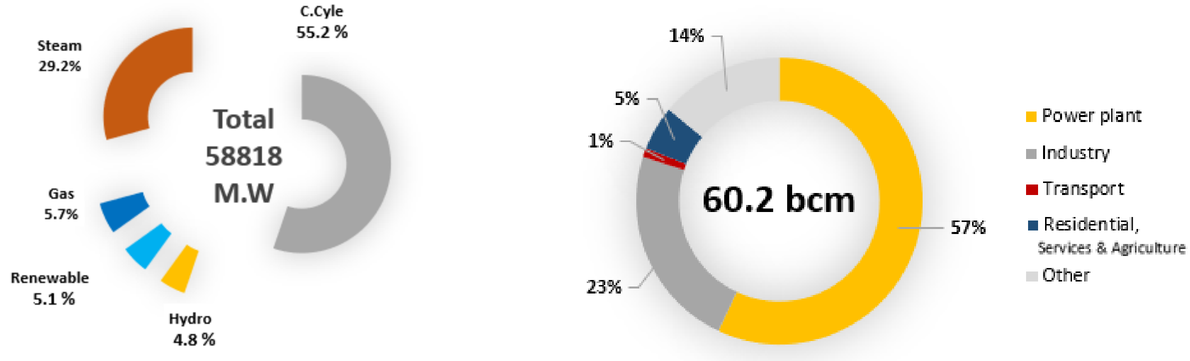

Fig. 3 Total installed capacity of 58.818 GW(e) in 2021 [6].

Fig. 2 Natural gas domestic consumption [7].

3. Boilers energy audit

In assessing steam power plant boiler efficiency, various statistical analysis methods are employed to evaluate performance and identify key factors influencing efficiency.

a) **Descriptive statistics** summarize boiler performance data, summarizing central tendencies and dispersion.

b) **Regression analysis** models the relationships between boiler efficiency and influencing factors like temperature, pressure, and fuel type, allowing prediction and identification of key predictors.

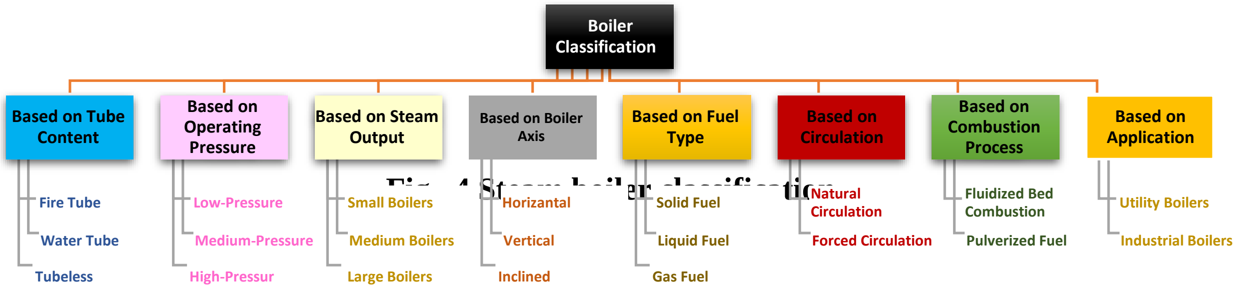

Fig. 4 Steam boiler classification

c) **Time series analysis** examines trends and forecasts future performance based on historical data.

d) **Correlation analysis** measures the strength and direction of relationships between variables, helping to identify the most influential factors.

e) **Principal Component Analysis (PCA)** reduces data complexity, highlighting the most significant variables.

f) **Hypothesis testing** validates the significance of observed improvements, ensuring they are not due to random variation.

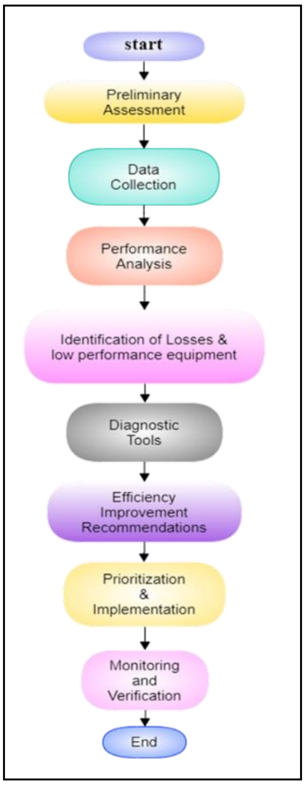

Fig. 5 Flow chart for a boiler energy audit strategy

Energy audit methodology can encompass statistical analysis as part of the comprehensive evaluation process. An energy audit for a boiler involves comprehensively examining the boiler system and its associated components to assess and optimize energy efficiency. The goal is to identify areas of energy wastage, improve performance, and reduce overall energy consumption. It is a valuable tool for organizations to analyze and understand their energy utilization, make informed decisions about budgeted energy distribution, plan for improved energy efficiency, and significantly reduce energy costs.

3.1.1 Energy audit strategy for boiler

Developing an effective strategy for a boiler energy audit involves a systematic approach to assess and optimize energy efficiency. Fig. 5 illustrates a flow chart for a boiler energy audit strategy. The following organized steps can be taken:

3.1.2 Define objectives: The goals and objectives of the energy audit of the boiler are reducing energy costs, enhancing efficiency, and minimizing environmental impact.

3.1.3 Information gathering:
Collect data on the boiler in the system, including specifications, operating conditions, and historical energy consumption.

3.1.4 Maintenance records review:
Examine maintenance records to identify patterns of issues or repairs, as regular maintenance is crucial for optimal boiler performance.

3.1.5 Combustion analysis:
Perform a combustion analysis to assess the efficiency of the combustion process, measuring parameters like flue gas composition and excess air.

3.1.6 Efficiency calculations:
Calculate overall efficiency, including combustion, thermal, and efficiency, to gauge the effectiveness of the boiler system.

3.1.7 Heat exchanger inspection:

Inspect heat exchangers for fouling, scaling, or corrosion and address any issues to improve heat transfer efficiency.

3.1.8 Blowdown and Heat Recovery:

Examine blowdown practices and identify opportunities for heat recovery to optimize efficiency.

3.1.9 Fuel quality and handling:

Assess the quality of fuel being used and ensure proper handling and storage.

3.1.10 Energy audit tools for boiler

The energy audit process commences with a walk-through visit and meetings with plant officials, including interviews with site operators. This initial step involves assessing facility utility bills (electricity, gas, water, etc.) and reviewing operating data to gain familiarity with building operations and identify evident areas of energy waste or inefficiency. Performing an energy audit for a boiler using various tools and equipment to gather data and assess the system's efficiency. Here are some standard tools used in a boiler energy audit:

- **Combustion analyzer:** To measure the efficiency of combustion and the levels of different pollutant gases as accurately as possible at the boiler's chimney.
- **Pressure probe:** Pressures are measured at various boiler locations using pressure probes.
- **Flow meter**: Monitor the flow rates of wet, saturated, and superheated steam, water flow, and fuel to calculate energy consumption and identify potential inefficiencies.
- **Clamp-on power meter:** To measure power consumption, current consumption, load factor, and power factor.
- **Smoke Tester:** Determines the opacity of flue gases, providing insights into combustion efficiency and potential issues.
- **Thermocouple sensor:** Thermocouple sensors are used to measure temperature at different locations.
- **Data logger:** Collect data over an extended period. Data loggers used to record data such as temperatures of different locations of the boiler, flue gas composition for a certain period, the power of motor consumption, etc., are needed to measure the dimensions of boilers and steam pipes as well as other essential parameters of the system. Some laboratory instruments are also required to determine the characteristic features of the fuel. Thermogravimetric analysis, ultimate analysis, and heating value determination are commonly used laboratory-related work needed in energy audits.

These strategies and tools, when used collectively, provide a comprehensive assessment of the boiler system's performance, helping to identify inefficiencies and areas for improvement in energy usage.

4. Boiler efficiency assessment

One of the critical components of any thermal power plant is the boiler, and a key performance parameter associated with it is "Boiler Efficiency." The efficiency of the boiler significantly impacts the overall performance of the electricity generation process. It has always been questioned due to the overheating impact on evaporation rate decrease over time, damage to the heat transfer system, and poor performance and maintenance. Even in new boilers, reasons such as deterioration of fuel quality, water quality, etc. This can lead to poor performance of the boiler [16].

The following two methods can be used to test the assessment of boiler efficiency:

I. Direct Method or Input Output Method.

II. Indirect Method or Heat Loss Method.

4.1. Direct method or input-output method

Boiler efficiency is defined as the percentage of the useful or gained energy of the working fluid (water and steam) to the energy input from the fuel. This is also known as the "input-output method" and is given in Eq. (1) as follows: [17].

$$Boiler\ Efficiency\ (\eta) = \frac{\dot{m}_{steam} \times C_p \times (T_s - T_{fw})}{\dot{m}_{fule} \times GCV} \times 100 \quad (1)$$

4.2. Indirect method or heat losses in boiler

The thermal efficiency of boilers generating superheated steam primarily depends on the amount of heat loss. The methods of heat loss vary based on factors such as the type of fuel, the type of boiler, operating conditions, and other relevant parameters. The solid fuels have the lowest efficiency, and the gaseous fuels have the highest efficiency. The efficiency of liquid fuel falls between solid and gaseous fuel [18]. Heat losses in a boiler system can be categorized into:

4.3. Heat losses from the stack gas:

Stack gas losses account for the most significant portion of energy loss in a boiler, with the assessment focusing on stack gas temperature and volume. Therefore, reducing these parameters will reduce heat loss. Meanwhile, the complete elimination of stack loss is economically unfeasible due to heat transfer. Measures to minimize stack gas heat loss include (optimizing excess air, maintaining a clean heat transfer area, and incorporating flue gas heat recovery systems). Reduction of excess air results in a decreased volume of stack gas, leading to lower flue gas velocity and allowing more time for heat absorption, thereby lowering the flue gas temperature. The percentage of heat loss due to dry flue gas is below in Eq. (2) [17].

$$The\ percentage\ heat\ loss = \frac{m * C_{pg} * (T_f - T_a)}{GCV\ of\ fuel} \times 100 \quad (2)$$

a) *Percentage of heat loss due to radiation and other unaccounted loss:*

The percentage of heat loss due to radiation and other unaccounted losses is impacted by radiation loss and convection loss. Actual radiation and convection loss are difficult to detect due to specific misalignments of the various surfaces, their inclination, airflow pattern, etc. For very small boilers, with a power of 10 MW, radiation and unbalanced losses may be between 1% and 2% of the total caloric value of fuel, while for the power of 500 MW, values between 0.2% and 1% are standard [14].

b) Steam leaks:

Steam leakage in a boiler refers to the unintended steam release from the system. These leaks can occur at various points, such as joints, valves, fittings, or damaged components within the boiler system. Steam leaks represent a significant issue, leading to energy losses, reduced efficiency, and increased operational costs.

c) Energy losses due to blowdown:

Blowdown energy losses in a boiler occur when a portion of concentrated boiler water is discharged to control impurity levels. This process removes solid particles such as sludge or sediments in the steam drum. The discharged hot water carries away both these particles and the thermal energy initially added for steam generation. The blowdown rate can vary based on factors like boiler type, operating pressure, water treatment, and makeup water quality, typically ranging from 4–10% of the boiler feed water flow rate [19]. Effective blowdown management is crucial for optimizing boiler performance and reducing energy wastage.

d) Fouling and scaling of boiler heat transfer surfaces:

Maintaining clean and efficient heat transfer surfaces in boilers is essential to optimize their performance. Here's a summary of the key points:

Fouling, scaling, and soot build-up: These factors act as insulators on heat transfer surfaces in boilers, reducing heat transfer efficiency. If left unattended, they can lead to increased flue gas temperatures and decreased heat transfer to the water in the boiler.

Effects on fuel consumption: Soot build-up on the fireside.

Tube failures: Scale deposits, often caused by calcium, magnesium, and silica in water supplies, may result in tube failures. It is emphasized that the heat transfer surfaces should be cleaned when scaling or fouling occurs.

Cleaning frequency: For boilers using gas and light oil, it is generally recommended to clean fireside surfaces once a year. However, more frequent cleaning may be necessary for boilers using heavy oil, potentially several times a year.

Preventive measures: To prevent scaling, steps should be taken to improve water treatment, such as enhancing water softening and maintaining a (TDS) level. For soot build-up, which is often a result of a defective burner or insufficient air for combustion, measures should be taken to repair or retune the combustion system [20].

e) Heat loss due to moisture in the fuel:

During combustion, the moisture or liquid water present in the fuel takes sensible and latent heat to become superheated steam. The superheated steam produced in the combustion chamber is at the added cost of the heat of combustion going to the chimney along with flue gas. The heat the moisture takes is directly proportional to the amount of moisture in the fuel. The heat loss due to moisture in fuel can be calculated using Eq. (3) [17].

$$\textit{Percentage of heat loss} = \frac{M \times \{2452.8 + C_p\,(T_f - T_a)\}}{GCV\ of\ fuel} \times 100 \qquad (3)$$

Where 2452.8: Latent heat of vaporization of water in the flue gases (J/kg) at typical temperatures found in combustion processes.

f) Heat loss due to incomplete combustion:

Incomplete combustion of carbon could occur due to a shortage of oxygen in the combustion chamber. The product of incomplete combustion is carbon monoxide, which liberates only 52% of the total heat in the fuel. Thus, products 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. (4) below [17].

$$\textit{The percentage of heat loss} = \frac{CO\ (ppm) \times 10^{-6} \times m_f \times 23746.8 \times 28}{GCV\ of\ fuel} \times 100 \qquad (4)$$

Where 23746.8: (J/mol) The amount of heat released per mole of CO 28 (g/mol): Molar mass of CO, used to convert moles of CO to kilograms.

g) Percentage of heat loss resulting from the evaporation of water during the combustion of hydrogen in the fuel:

The percentage of heat loss attributed to water's evaporation resulting from hydrogen in the fuel can be calculated using Eq. (5) below [16].

$$The\ percentage\ of\ heat\ loss = \frac{9 \times H_2 \times \{245.8 + C_p\,(T_f - T_a)\}}{GCV\ of\ fuel} \times 100 \quad (5)$$

Where H_2 is kg of hydrogen in 1 kg of fuel.
9: This factor comes from the stoichiometry of hydrogen burning (combustion of 1 kg of hydrogen produces about 9 kg of water).
245.8 (kJ/kg): the latent heat of vaporization of water at a specific condition.

h) Percentage of heat loss caused by moisture content in the air:

The ambient air naturally includes water vapor. During combustion, the water vapor in the combustion air transforms into superheated steam, utilizing a portion of the combustion heat. Consequently, moisture in the air leads to a loss of heat. The loss percentage attributed to the moisture in the air can be determined using Eq. (6) [16].

$$Percentage\ of\ heat\ loss = \frac{AAS \times Humidity \times C_p \times (T_f - T_a)}{GCV\ of\ fuel} \times 100 \quad (6)$$

i) Percentage of heat loss attributed to unburnt carbon in both bottom and fly ash:

The carbon content in ash represents a direct loss of useful fuel carbon expected to be burned in the combustion chamber. The loss percentage attributed to the moisture in the air can be determined using Eqs. (7), (8) [16].

$$Percentage\ of\ heat\ loss = \frac{Total\ ash\ collected\ K_g\ \ of\ fuel\ burnet \times GCV\ of\ bottom\ ash}{GCV\ of\ fuel} \times 100 \quad (7)$$

$$Percentage\ of\ heat\ loss = \frac{Total\ ash\ collected\ K_g\ \ of\ fuel\ burnet \times GCV\ of\ fly\ ash}{GCV\ of\ fuel} \times 100 \quad (8)$$

Thus, the efficiency of the boiler can be calculated in Eq. (9) and can be described through the energy flow diagram as shown in Fig. 6:

$$Efficiency\ of\ Boiler\ (\eta) = 100 - (all\ aforementioned\ percentage\ errors) \quad (9)$$

5. Environmental assessment of boiler

Boilers release various harmful gases and particulate matter through their stacks. Additionally, solid fuel-fired boilers produce bed and fly ashes, contributing to the emission of particulate matter and pollutant gases. The primary gaseous pollutants include carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur dioxide (SO_2), carbon monoxide (CO), polynuclear aromatic hydrocarbons (PAHs), lead, hydrogen chloride (HCl), cadmium, mercury, dioxins, furans, among others [21].

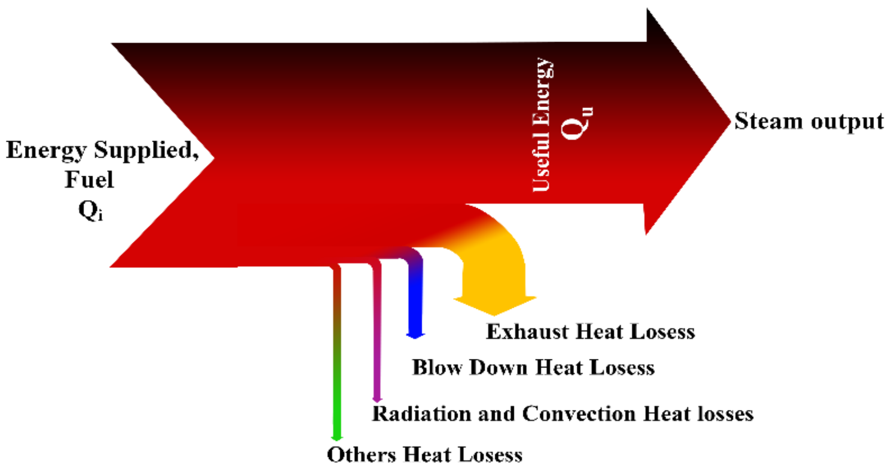

Fig. 6 Sanky diagram of a boiler [5]

These pollutants exert varied effects on the environment and human health. They significantly contribute to climate change, acid rain, and the greenhouse effect. The environmental assessment of a boiler involves evaluating its impact on the environment throughout its lifecycle. Fig. 7 shows the key aspects considered in such an assessment:

Emissions: Assessing combustion emissions (CO_2, NO_x, SO_2) to understand air pollution and greenhouse gas contributions. Chandra et al. [21] studied the environmental impact of using different fuels in boilers, demonstrating significant improvements. The study showed a decrease in CO_2 emissions by 15-20% when switching to more sustainable fuels. Nitrogen oxide emissions were reduced by 10-15%, enhancing air quality. Sulfur oxide emissions decreased by 20-25%, mitigating the impacts of acid rain. Particulate matter emissions were lowered by 5-10%, improving overall air quality and health benefits.

Efficiency: Evaluating the boiler's ability to convert fuel to heat efficiently, reducing fuel consumption and emissions per unit of energy.

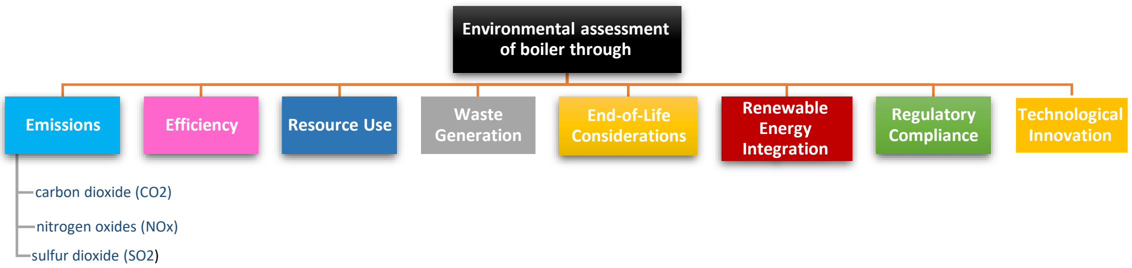

Fig. 7 Overall evaluation of the environmental impact of a boiler

6. Research gap and future challenges

- The existing literature mainly focuses on sources of heat loss, evaluates the performance test for boilers using direct and indirect methods, and demonstrates that supply-air humidification is advantageous for enhancing overall boiler efficiency. Additionally, heat losses in boilers due to technical and operating conditions and heat loss in boilers fired with gaseous and oil fuels occur through the chimney, the external surface of the boiler to the atmosphere, and due to incomplete combustion [9, 10, 11, 14].
- Further study shall be done to optimize the parameters like boiler feed water quality, burner management, and fuel quality for tube life, which involves exploring advanced materials for enhanced impurity, scales, sludges, and salt removal in boiler water before use in a steam power plant boiler.
- Integrating renewable energy sources and advanced control systems could offer new pathways for enhancing boiler efficiency and environmental performance.
- What are the effects of implementing advanced control systems, such as AI and IoT, on the operational efficiency of steam power plant boilers?
- Additional research is required to explore the potential of other waste heat recovery strategies and their integration with natural gas-fired boilers.

7. Conclusion

This study identified several key heat loss mechanisms in the steam power plant boiler. The major sources of heat loss included flue gas loss, radiation loss, blowdown loss, and heat loss due to moisture in the fuel. Specifically, flue gas loss was the most significant, accounting for approximately

20% of total heat loss, followed by radiation loss at 5%, blowdown loss at 3%, and moisture in the fuel at 7% [5]. Table 2 summarizes the main findings, efficiency improvements, and emission reductions from various steam power plant boilers studies. Wang et al. [10] achieved a 5 – 8 % improvement in efficiency by investigating co-combustion characteristics, resulting in a CO_2 emission reduction of 0.7 million tons per year. This finding is comparable to Chandra et al. [21], who achieved a 7-12 % improvement in efficiency by using different fuels in boilers, demonstrating significant improvements, reducing CO_2 emissions by 0.5-1 million tons per year. While Liu et al. Applied model predictive control to biomass boilers, achieving fast response and stability, reported a CO_2 reduction of 1 million tons annually.

Table 2 A summary of the research performed on the main findings, efficiency improvements, and emission reductions from various studies on steam power plant boilers.

STUDY	MAIN FINDINGS	EFFICIENCY IMPROVEMENT	EMISSION REDUCTION (MILLION TONS CO_2 PER YEAR)
wang et al. 2023), [10]	Investigation on Co-combustion characteristics and NOx emissions of coal	5-8% improvement in efficiency	0.7 million tons CO2
Dwivedi et al. (2021) [14]	Improved energy efficiency and minimized heat loss during boiler operation	10 – 12 % improvement in efficiency	0.5 – 1 million tons CO_2
Sun, y., zhang, y., & jiang, z. (2023), [12]	CFD-based air distribution control strategies improve combustion efficiency in supercritical boilers.	-	1 million tons CO_2
liu, s., et al. (2023) [11]	Applied model predictive control to biomass boilers, achieving fast response and stability.	-	1 million tons CO_2
chandra et al. (2013), [21]	Studied the environmental impact of using different fuels in boilers, demonstrating significant improvements	7-12% improvement in efficiency	0.5-1 million tons per year

Sun, Y., Zhang, Y., & Jiang, Z. [12] found that CFD-based air distribution control strategies in supercritical boilers could significantly reduce CO_2 emissions by 1 million tons per year, demonstrating the effectiveness of advanced control strategies.

This showed that energy efficiency optimization is pivotal for reducing energy intensity, preserving resources, and mitigating environmental impact by reducing CO_2 emissions and minimizing waste. The study explores various sources of heat loss and inefficiencies within boiler systems, exploring innovative strategies such as using energy audits. Effective blowdown management is crucial for optimizing boiler performance and reducing energy waste. Assessing the quality of fuel being used and ensuring proper handling and storage can contribute to improving efficiency.

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