A SYSTEMATIC APPROACH TO ENERGY MANAGEMENT IN AN INDUSTRIAL STEAM BOILER PLANT
Improving Energy Efficiency, Economic, and Environmental Performance

by

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To achieve optimal performance in industrial steam boiler plants, it is necessary to reduce energy consumption per unit of product. By conducting a systematic assessment of the performance of steam boiler plants and assessing the potential for improving energy efficiency, it is possible to approach the correct selection and implementation of appropriate measures and technical solutions, which can result in significant energy savings, improvement of production quality, reducing production costs and mitigating negative environmental impacts. The subject of consideration in this paper is a steam boiler plant in the industrial sector, where the main purpose is, with comprehensive systematic approach of the current situation, to consider the possibilities for effective implementation of measures and to analyse the achieved effects that contribute to the efficiency and sustainability of the overall system.

Key words*: energy efficiency, energy performance, energy savings, industrial sector, steam boiler plants*

Introduction

The various environmental and economic problems caused by irrational energy consumption and inadequate energy management procedures in industrial steam boiler plants are increasing as industrial plants operate more intensively and energy demand rises. The industrial sector contributes to 37% of total world energy consumption [1]. Industrial steam boiler plants account for an extremely significant share of the total consumption of energy resources on a global scale. In fact, about 40% of the total fuel consumed in the industrial sector is used for steam generation [2].

The importance of energy efficient technologies continues to grow but at the same time their technical potential is still far from the theoretical one which indicates opportunities for further improvement of energy efficiency in all energy sectors and at all levels of energy consumption [3]. Also, mostly due to other priorities, many industrial companies lack appropriate methods to effectively adress energy efficiency in a systematic, comprehensive and practical way which is a serious limiting factor for efficiency enhancement [4]. The establishment of an energy management system, as a comprehensive way of organised management of energy flows is a proper approach to achieve energy and financial savings and reduce environmental impact [5].

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The findings in [6], indicate that energy efficiency varies significantly across sectors, mainly due to outdated technology and inadequate maintenance practices. Additionally, there are prevalent misconceptions regarding the importance of energy management across various sectors. Implementing efficient energy management strategies can enable companies to reduce costs, promote new technological solutions and maintain a competitive edge in the market. The research [7] emphasizes the importance of regular energy audits to identify areas of heat loss and improve operating efficiency.

There is a notable lack of awareness and insufficient information among individuals managing and working in various industrial facilities regarding the equal significance of the three key components: energy, economic, and environmental factors. Numerous instances, both theoretical and practical, illustrate a tendency to prioritize the economic aspect, often neglecting or minimally considering the energy component, and even less so the environmental aspect. Frequently, energy analyses are conducted on industrial steam boiler systems before and after implementation of appropriate energy efficiency measures without adequately considering or establishing a balance with the environmental and economic factors. Such patterns are prevalent in a multitude of contemporary studies that restrict their scope to either energy and economic or energy and environmental performance evaluations.

Considering that steam boiler plants and systems represent the most significant energy consumers in various production facilities, accounting for over 80% of their energy consumption [8], optimising the performance of steam boilers and systems is necessary to reduce energy consumption and achieve positive environmental and economic effects.

As previously mentioned, the literature review reveals a limited number of studies that adopt a systematic approach to improving energy efficiency in steam boiler plants in the industrial sector, with particular emphasis on the integration of energy, environmental, and economic aspects. This paper specifically targets the achievement of favorable results in these three areas through the systematic application of energy-efficient strategies. It outlines a robust framework for energy management in steam boiler plants that is sustainable, maintains product quality and ensures compliance with industry standards, focusing on opportunities to improve energy efficiency, reduce steam generation costs, and decrease CO_2 emissions.

Systematic assessment of the existing condition and determination of energy performance indicators

The steam boiler utilized for providing process heat to the industrial facility is a horizontal, three-pass design, featuring fire tube heat exchangers and a burner with a rotating cap. This boiler operates on natural gas as its fuel source. The principal schematic of the boiler plant is illustrated in fig. 1, offering a detailed lay-out of the steam boiler. The main specifications of the boiler are:
– Boiler capacity: 4.93 MW.
– Drum pressure: 11 bar.
– Steam outlet pressure: 9.85 bar.
– Steam outlet temperature: 179.2 °C.
– Feedwater temperature: 75 °C.
– Dimensions (diameter × length): 2400 mm × 7400 mm.

The drum pressure is measured by using a pressure gauge, 9 in fig. 1, installed in the boiler with an uncertainty of ±2%. The steam outlet pressure is measured by using a pressure transmitter, 11 in fig. 1, with an uncertainty of ±0.5%. Steam outlet temperature and feedwater temperature are measured using a thermocouple, 8 in fig. 1, with an uncertainty of ±1 °C. These uncertainties are consistent with measurements from previous case studies [2]. The flow dynamics within the boiler and through the heat exchangers are illustrated in fig. 2.

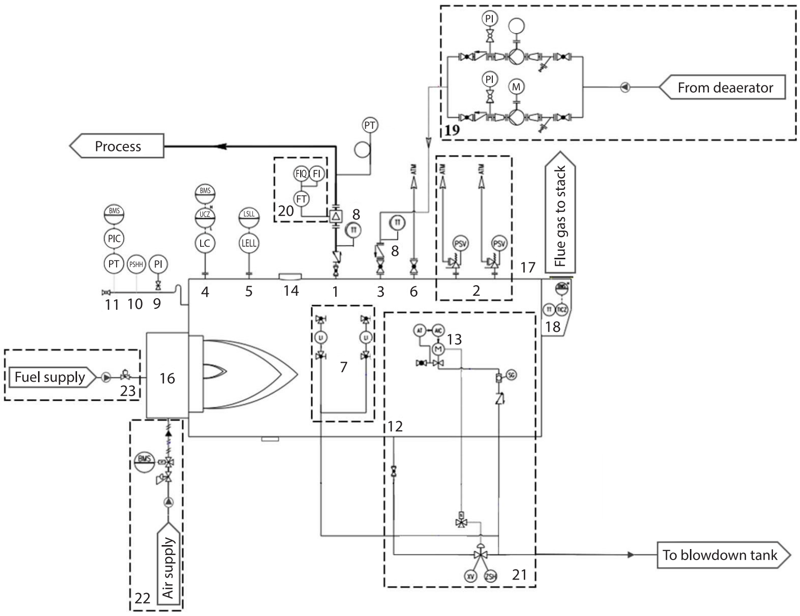

Figure 1. Principal schematic of the steam boiler plant; *1 – main steam valve, 2 – pressure safety valves, 3 – feed water valve, 4 – water level control, 5 – water level alarm, 6 – vent valve, 7 – water level indicators, 8 – thermocouple, 9 – pressure gauge, 10 – pressure switch, 11 – pressure transmitter, 12 – bottom blowdown valve, 13 – surface blowdown valve, 14 – man inspection hole, 15 – head inspection hole, 16 – burner, 17 – flue gas outlet, 18 – flame inspection hole, 19 – feedwater system, 20 – steam flow meter, 21 – blowdown system, 22 – air supply system, and 23 – fuel supply system*

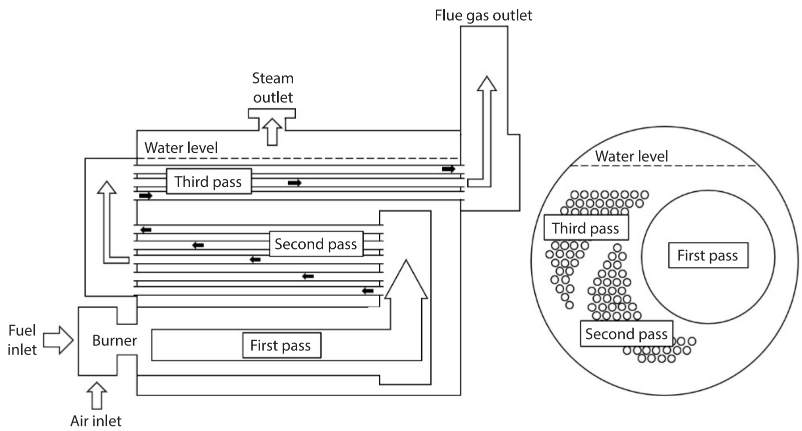

Figure 2. The flow dynamics within the boiler and through the heat exchangers

Energy surveys identify opportunities for investments that enhance energy efficiency and they reveal irrational use of energy and energy efficiency improvement possibilities [9]. As a part of the systematic approach for implementing measures aimed at improving the performance of the steam boiler plant, a condition survey is conducted.

The condition survey provides a comprehensive overview of the entire steam boiler plant. This thorough orientation helps to identify key areas of energy consumption and the factors influencing those usages. The survey aids in uncovering potential energy management opportunities that warrant further exploration and it highlights immediate energy-saving opportunities that can be implemented with minimal additional evaluation.

This assessment is based on a system of four states (from 0 to 3), where 3 stands for a state reflecting high energy efficiency and 0 for a state reflecting low energy efficiency [10]. The results provide qualitative data about the boiler plant, which is useful for defining the quantitative rating, thereby simplifying the selection of energy efficiency measures. The rating is a numerical score for the survey observation that helps to determine the scope and urgency of any corrective actions. This score indicates the urgency of implementing corrective measures based on the scale presented in tab. 1.

The performed analysis of the existing condition of the steam boiler plant is shown in tab. 2, according to which the final result, *i.e.* the rating of the entire system, is determined.

Table 1. Dependency of the measures to be implemented on the obtained rating [10]

Range of score, [%]	Action required
0-20	Immediate corrective action required
20-40	Urgent corrective action required
40-60	Corrective action required
60-80	Evaluation for potential improvement required
80-100	No corrective action required

Equation (1) is used to evaluate the existing condition of the steam boiler plant:

$$\text{Final rating} = \frac{100\% \cdot \text{Total number of points}}{\text{Number of elements} \cdot \text{Maximum number of points}} \tag{1}$$

Based on the results presented in tab. 2 and according to eq. (1), the rating of the steam boiler plant is 45%. This indicates that corrective measures are required to improve energy efficiency.

Before proceeding with the implementation of measures to improve the efficiency of the steam boiler plant, it is necessary to identify and determine the key indicators of energy, economic, and environmental performance that are used to assess its performance and potential for improvement.

The key parameters characterizing the current state of the steam boiler plant are shown in tab. 3.

Table 4 outlines the indicators for evaluating the performance of the steam boiler plant. To accurately assess these indicators, it is necessary to consider several key data points:

– The number of operating hours, t, of the steam boiler plant, is 6048 hour per year.
– Natural gas is used as fuel, with a density, ρ_f, of 0.68 kg/m^3, and a CO_2 emission factor, EF_{CO_2}, of 0.19 kg CO_2 per kWh.
– The unit price of natural gas, c_f, is 0.7 €/m^3, equivalent to 0.065 €/kWh, which is variable based on the determinations made by energy regulatory authorities.

Table 2. Assessment of the existing condition of the steam boiler plant

Evaluation criteria		Insulation in good condition	Insulation in average condition	Insulation in poor condition	Flanges, valves and regulators are insulated	There are no steam leaks	There are some steam leaks	There are many steam leaks	Automatic control of the boiler	Standard operating procedures apply	Steam flow meter	Fuel flow meter	Feed water flow meter	Flue gas-flow meter	A definite schedule for preventive maintenance is followed	The equipment is maintained or repaired only in case of malfunction	Flue gas waste heat recovery system	Condensate return system	Blowdown heat recovery system	Total number of points
Number of element	Points / Maximum number of points = 20	2	1	0	2	2	1	0	1	1	1	1	1	1	1	0	3	2	2	
1	Steam boiler plant	Before the implementation of the proposed measures																		
			1				1		1	1	1	1	1	1	1					9
		After the implementation of the proposed measures																		
			1			2			1	1	1	1	1	1	1		3	2	2	17

Table 3. Characteristic parameters of the steam boiler plant

Parameter	Determined by	Value
Generated steam mass-flow rate, q_s [kgs^{-1}]	Measurements from the steam flow meter	2
Specific enthalpy of saturated steam, i''_s [kJkg^{-1}]	A vapor pressure table for a steam pressure, p_s, of 10 bar	2.778
Fuel flow rate, q_f [m^{3}s^{-1}]	Measurements from the fuel flow meter	0.165
Feedwater flow rate, q_{fw} [m^{3}s^{-1}]	Measurements from the feedwater flow meter	0.002
Specific enthalpy of feedwater, i'_{fw} [kJkg^{-1}]	A feedwater temperature table for a temperature, t_{fw}, of 75 °C	314
Gross calorific value of the fuel, H_g [kJm^{-3}]	A chart on the specifications of the natural gas	38720
Flue gas mass-flow rate, q_{fg} [kgs^{-1}]	Measurements from the flue gas-flow meter	3.55

Table 4. Energy, environmental and economic performance indicators

Indicator	Determined by	Value
Overall boiler efficiency, η [%]	Direct method	77.13
Combustion efficiency, η_c [%]	Depending on the amount of excess air, A, of 36.5% and the temperature of the exhaust flue gases, t_{fg}, of 200 [°C]	78.85
Condensate returned as feedwater, x_c [%]	Performing a heat balance for the feedwater, condensate water and make-up water	86
Blowdown mass-flow rate, q_b [kgs^{-1}]	Depending on the conductivity, κ, of the boiler feedwater	0.083
Steam leaks, q_{sl} [kgs^{-1}]	On-site measurements performed	0.04
Carbon dioxide emissions, EM_{CO_2} [kg CO_2 per year]	Calculation based on the carbon dioxide emission factor, EF_{CO_2}	7341728
Steam generation costs, SGC [€ per tonne]	Calculation based on the unit price of the natural gas, c_f	57.85

According to the direct method [11], the overall energy efficiency, η, is equal to the ratio of the annual energy output, Q_l, and the annual energy input, Q_F. Equation (2) is used to determine the total energy output on an annual basis:

$$Q_l = q_s\left(i''_s - i'_{fw}\right)t \tag{2}$$

By substituting the appropriate values, it is determined that the annual energy output for the considered steam boiler plant amounts to 29804544 kWh.

The annual fuel energy required for the operation of the boiler plant is:

$$Q_F = q_f H_g t \tag{3}$$

By applying eq. (3), a value of 38640672 kWh is determined.

From an environmental point of view, by using eq. (4) it is possible to calculate the total CO_2 emissions, EM_{CO_2}, generated by the operation of the plant on an annual basis:

$$EM_{CO_2} = Q_F EF_{CO_2} \tag{4}$$

Therefore, the annual CO_2 emissions resulting from the operation of the steam boiler plant amount to 7341728 kg CO_2.

In terms of economic performance, the SGC, are determined [2]:

$$SGC = \frac{q_f(\tau)c_f}{q_s(\tau)} \tag{5}$$

Therefore, if the number of annual working hours of the steam boiler plant is also taken into consideration, total steam generation costs, TC, of 2519113 € per year are determined.

Implementation of energy efficiency measures and analysis of the achieved benefits

After the assessment of the existing state of the steam boiler plant and the determination of the energy, environmental, and economic performance indicators, it is possible to approach the implementation and analysis of appropriately selected measures and solutions to improve energy efficiency, and then to evaluate the achieved benefits.

Elimination of steam leaks

It is common for steam generated in a steam boiler to leak due to openings of different sizes in the individual components of the steam boiler plant. According to long-term measurements it was determined that, in the considered steam boiler plant, with a steam pressure, p_s, of 10 bar, steam leakage, q_{sl}, of 0.04 kg/s occurs through measured openings with an average diameter of 7 mm. These steam losses lead to thermal energy losses, resulting in an increased overall consumption of energy, fuel, and financial resources, as well as heightened CO_2 emissions. Therefore, it is recommended to eliminate the steam leaks by repairing and sealing the previously identified openings. Repairing existing components is a more efficient approach in terms of time and cost compared to procuring new parts [12]. In this context, welding technologies were applied to repair the existing openings. Prior to the repair process, a visual inspection and penetrant testing were carried out.

With eliminating the steam leaks, significant benefits could be achieved, annual fuel savings of 81012 m^3, a reduction in energy consumption of 871329 kWh per year, a decrease in CO_2 emissions of 165553 kg CO_2 per year and financial savings of 56708 € per year.

Condensate return

By performing a heat balance [8], the percentage representation of the condensate, as well as of the make-up water, in the total amount of feedwater was previously determined, as shown in tab. 3. With a condensate temperature, t_c, of 83 [ºC], a make-up water temperature, t_{mu}, of 25 [ºC], and a feedwater temperature, t_{fw}, of 75 [ºC], it can be concluded that 86% of the condensate is returned as feedwater to the boiler. This indicates that 0.00172 m^3/s of the boiler feedwater comprises condensate.

Consequently, the amount of heat, Q_{mu}, required to raise the temperature of 1 kg of cold make-up water from 25 [ºC] to 83 [ºC], given a specific heat capacity, $c_{p,w}$, of 4.1785 kJ/kgK, is 242 kJ/kg.

Equation (6) is applied to determine how much energy, Q_{cr}, is required to replace the heat in the make-up water:

$$Q_{cr} = q_c Q_{mu} t \tag{6}$$

It is determined that 9063 GJ are required annually, or if the efficiency of the boiler, η, is taken into consideration, this requirement increases to 11750 GJ, which equates to 3263889 kWh needed to replace the heat in the make-up water. Accordingly, a reduction in CO_2 emissions of 620139 kg CO_2 per year would be achieved.

In terms of total financial savings, TFS, they represent the sum of energy cost savings, *i.e.* fuel savings, *FS*, 212153 € per year, water cost savings needed to replace irreversible condensate, *WS*, 36700 € per year, as well as the cost savings for wastewater treatment, *WTS*, 10860 € per year. The unit price of water, c_w, is therefore, 0.98 € per m^3, and the unit costs for wastewater treatment, c_{wt}, are 0.29 €/m^3. The required water flow rate, q_w, is 37449 m^3 per year, calculated according to the equation: $q_w = q_c(1/\rho_w)t$. It is crucial to highlight that the price of water fluctuates over time and is influenced by various regulations governing the use of water resources within the industrial sector.

Blowdown heat recovery

The conductivity of the boiler water, κ_{bw}, is 2500 μS/cm. Meanwhile, the feedwater conductivity, κ_{fw}, is 100 μS/cm. These values are in accordance with the manufacturer's guidelines for maintaining best practices in the operation of low pressure boilers. Typically, the boiler blowdown rate, x_b, is determined based on the total dissolved solids in the water, *TDS*. However, since the ratio of conductivity, κ, to total dissolved solids, *TDS*, remains constant for a certain volume of water [2], in this case, the calculation can be performed using the available data on water conductivity:

$$x_b = \frac{\kappa_{fw}}{\kappa_{bw} - \kappa_{fw}} \times 100\% \tag{7}$$

Therefore, the blowdown rate is calculated to be 4.16% or, considering the total generated steam mass-flow rate, q_s, a blowdown mass-flow rate of 0.083 kg/s is determined by applying the equation: $q_b = q_s x_b$. According to eq. (8), the amount of heat that can be recovered from the blowdown is:

$$Q_b = q_b i'_{10bar} \tag{8}$$

Applying eq. (8), a heat quantity of 82.107 kW is determined.

Equation (9) is used to calculate the generated flash steam mass-flow rate during the blowdown process, q_{fs}, as the pressure through the blowdown valve decreases from 10 bar, at the beginning of the valve, to 0.4 bar, at the end of the valve:

$$q_{fs} = q_b \frac{i'_{10bar} - i'_{0.4bar}}{r_{0.4bar}} \tag{9}$$

Equation (10) can be used to calculate the energy recovered by generating flash steam during the blowdown process, Q_{fs}:

$$Q_{fs} = q_b (i'_{10bar} - i'_{0.4bar}) \tag{10}$$

It is determined that 36.960 kW of the energy contained in flash steam can be recovered.

The thermal energy contained in the condensate returned as feedwater, Q_c, can also be utilized. The heat exchanger applied reduces the temperature to 20 °C. According to eq. (11), the calculation for determining this amount of energy is carried out:

$$Q_c = q_b \left(1 - \frac{x_{fs}}{100}\right)(i'_{0.4bar} - i'_{20°C}) \tag{11}$$

It is determined that 15.673 kW of the energy in the condensate can be utilized by returning it as feedwater. The total energy savings, Q_{bhr}, are calculated as a sum of the energy contained in the flash steam generated during the blowdown process, Q_{fs}, and the energy contained in the condensate returned as feedwater, Q_c, thus determining a total value of 68.239 kW.

From the ratio Q_{bhr}/Q_b, it is concluded that 83% of the energy in the blowdown can be recovered. The researchers in [13] achieved a comparable outcome of approximately 83.16% by implementing a blowdown heat recovery system aimed at enhancing the energy efficiency of a steam boiler within a petroleum refinery, thereby substantiating the validity of this technical approach.

Based on the analysis, it can be summarized that the implementation of this measure results in achieved energy savings of 412710 kWh per year, a reduction in CO_2 emissions by 78415 kg CO_2 per year, and annual financial savings of 26826 €.

Installation of a waste heat recovery system

Considering that heat exchangers have been proposed as one of the best systems for recovering energy [14], the steam boiler plant being evaluated incorporates an economizer designed to capture heat from the exhaust gases. Equation (12) is used to calculate the recoverable heat from the flue gas waste heat recovery system, Q_{fg}, which can be utilized for additional heating of the boiler feedwater:

$$Q_{\text{fg}} = q_{\text{fg}} c_{p,\text{fg}} \Delta T \tag{12}$$

With a flue gas mass-flow rate, q_{fg}, of 3.55 kg/s, a specific heat capacity, $c_{p,\text{fg}}$, of 1.0130 kJ/kgK, and a flue gas temperature reduction, ΔT, from 200-120 °C, which is, 80 °C, savings of 287.692 kW, can be achieved, or, if the boiler efficiency, η, is also taken into consideration, 372.996 kW. With 6048 working hours throughout the year, the energy savings amount to 2255881 kWh.

The reduction of CO_2 emissions after the implementation of the proposed measure amounts to 428617 kg CO_2 per year. Additionally, by reducing the temperature of the flue gases, the combustion efficiency increases from 78.85%-80.25%. This enhancement is favorable since various studies indicate that combustion efficiency should exceed the value of 80%.

The total financial savings for the purchase of fuel are estimated to be 146819 € per year. Non-etheless, taking into account that this action requires substantial technical improvements, it is imperative to analyze the pay-back period of the investment. For example, in [11] the authors find that the pay-back period for the waste heat recovery system linked to a specified steam boiler is one year, which is economically justified when all relevant factors are taken into consideration.

Analysis of the achieved benefits and further considerations

Figure 3 summarizes the results obtained from the proposed measures. The most significant enhancement in the performance of the steam boiler plant was achieved by returning the condensate as feedwater, *i.e.* by utilizing its heat through a heat exchanger. In this case, the overall energy efficiency, η, reached 84.25%, representing the most notable improvement compared to the other measures.

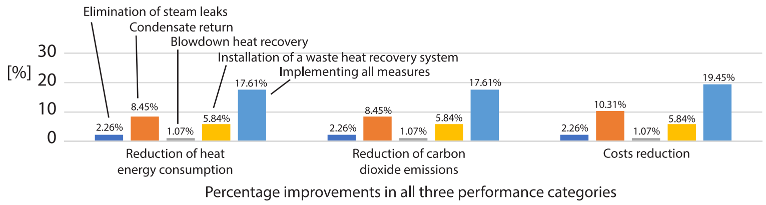

Figure 3. A summary of the improvements achieved in the performance of the steam boiler plant due to the application of the energy efficiency measures

The implementation of all four measures leads to an optimal performance improvement. Thermal energy consumption decreases by 17.61%. The CO_2 emissions are reduced by 17.61%. Steam generation costs decline by 19.45%. The energy efficiency increases from 77.13-93.62% indicating the positive impact of systematically applying the previously selected measures.

By reapplying tab. 2 and eq. (1), following the implementation of all measures, the performance rating would improve from 45-85%. This confirms the previously analysed benefits and enhances the energy efficiency of the steam boiler plant. However, a rating of 85% indicates that there are still opportunities to further optimize the plant's operation.

Regarding the further optimization of the steam boiler plant, implementing a comprehensive energy management system, such as the ISO 50001 standard, can contribute to significant improvements from energy, economic and environmental perspectives. According to [15], following the guidelines of the ISO 50001 standard, a reduction of 20% in natural gas consumption can be achieved.

According to an exergoeconomic analysis of an existing steam boiler plant [16], the steam generation costs mainly depend on fuel cost (nearly 90%) and in smaller amount on capital investment costs. Taking this into account, the application of exergy analysis in conjunction with energy analysis will offer more detailed and valuable insights into the energy, economic and environmental performance. Furthermore, the authors in [17] emphasize that alternative fuels like biodiesel, combined with other technologies, improve energy and exergy efficiency in industrial steam boiler plants. Also, [18] underscores the importance of innovative fuels, such as biodiesel with nanoparticles, in minimizing environmental impact. One potential action to improve the energy efficiency of the steam boiler plant is to evaluate the replacement of the energy source. This would entail substituting the natural gas with a more economically advantageous and justifiable option.

The implementation of a systematic approach to energy efficiency measures in industrial steam boiler plants, combined with advanced automated systems for load optimization and fuel redistribution, offers significant economic and environmental benefits [19]. The study in [20] examined the potential for energy savings and emission reductions in industrial boilers, emphasizing the implementation of variable speed drives (VSD). By combining VSD with techniques like condensate heat recovery and flue gas heat recovery, a holistic strategy could be established to further improve energy efficiency, minimize emissions, and enhance overall system performance. According to [21], the integration of advanced technologies such as simultaneous over-fire air and flue gas re-circulation can lead to significant reductions in NO_x emissions and improvements in combustion efficiency. Non-etheless, there is a lack of references concerning their use in boilers that operate on natural gas. This presents an opportunity to investigate the effectiveness of these technologies in a natural gas-powered steam boiler plant, such as the one considered in this paper, and evaluate the outcomes.

Most of the referenced studies support the notion that an integrated approach, addressing energy, economic and environmental aspects, is crucial for enhancing steam boiler performance. This approach has proven to be energy-efficient, economically viable and environmentally justified.

Conclusions

Through a systematic assessment of the existing condition and an appropriate selection and implementation of measures to improve energy efficiency across various types of steam boiler plants in the industrial sector, considerable energy savings can be realised. These savings are accompanied by a reduction in total annual steam generation costs and a decrease in overall CO_2 emissions, which are key indicators of energy, economic and environmental performance. By implementing the well-defined and analysed measures for the steam boiler plant discussed in this paper, reductions of approximately 20% can be achieved across all three performance categories. This indicates the effectiveness of the measures taken, which is also confirmed by the significant improvement in energy efficiency. The evaluation of the steam boiler plant after implementing the proposed measures reveals further opportunities for the systematic implementation of energy-efficient technical solutions, which could lead to additional improvements in overall performance.

Future research initiatives, as previously noted, may focus on the integration of technologies such as real-time monitoring and sophisticated automated systems. Additionally, efforts to significantly reduce NO_x emissions, explore alternative fuels, and incorporate renewable energy sources will be paramount. Essential research domains will involve conducting cost-benefit analyses and developing a robust energy management framework that could improve the sustainability of industrial steam boiler plants. This aligns with global objectives for energy transition and strategies for climate change mitigation, while also addressing the challenges posed by the implemented measures. Such challenges include the requirement for considerable upfront investments in technologies like heat exchangers and waste heat recovery systems, the resource demands of maintaining systems like blowdown and condensate recovery, various technical difficulties throughout the implementation phase and operational complexities encountered during the implementation that affect production efficiency. Future studies would benefit significantly from a detailed assessment of the pay-back period for energy efficiency improvements, alongside a broader analysis of GHG emissions that encompasses a wider array of pollutants beyond just CO_2.

While the adoption of the proposed interventions and the improvements achieved differ among various steam boiler plant types and are contingent upon numerous factors – particularly the differing regulations in individual countries and the volatility of resource prices – the results obtained and the comparative analysis with related studies demonstrate that the measures are suitable for the majority of industrial steam boiler facilities, producing favorable energy, economic, and environmental outcomes.

Nomenclature

c_f – unit price of fuel, [€ per m^3]
$c_{p,fg}$ – specific heat capacity of the flue gases, [kJkg^{-1}K^{-1}]
$c_{p,w}$ – specific heat capacity of water, [kJkg^{-1}K^{-1}]
c_w – unit price of water, [€ per m^3]
c_{wt} – unit costs for wastewater treatment, [€ per m^3]
EF_{CO_2} – carbon dioxide emission factor, [kg CO_2 per kWh]
EM_{CO_2} – annual carbon dioxide emissions from the steam boiler plant, [kg CO_2 peryear]
FS – fuel cost savings, [€ per year]
H_g – gross calorific value of the fuel, [kJm^{-3}]
i''_s – specific enthalpy of saturated steam, [kJk^{-1}]
$i'_{0.4bar}$ – specific enthalpy of water at a pressure of 0.4 bar, [kJkg^{-1}]
i'_{10bar} – specific enthalpy of water at a pressure of 10 bar, [kJkg^{-1}]
$i'_{20°C}$ – specific enthalpy of water at a temperature of 20 °C, [kJkg^{-1}]
i'_{fw} – specific enthalpy of feedwater, [kJkg^{-1}]
p_s – steam pressure, [bar]
Q_b – heat that can be recovered from the blowdown, [kW]
Q_l – annual energy output, [kWh per year]
Q_{bhr} – total energy savings with blowdown heat recovery, [kW]
Q_c – energy contained in the condensate returned as feedwater, [kW]
Q_{cr} – energy required to replace the heat in the make-up water, [GJ per year]
Q_F – annual energy input, [kWh]
Q_{fg} – amount of heat that can be recovered by installing a flue gas heat recovery system, [kW]
Q_{fs} – energy contained in the flash steam generated during the blowdown, [kW]
Q_{mu} – amount of heat required to raise the temperature of 1 kg of cold make-up water, [kJkg^{-1}]
q_b – blowdown mass-flow rate, [kgs^{-1}]
q_c – condensate mass-flow rate, [kgh^{-1}]
q_f – fuel flow rate, [m^{3}s^{-1}]
q_{fg} – flue gas mass-flow rate, [kgs^{-1}]
q_{fs} – generated flash steam mass-flow rate, [kgs^{-1}]
q_{fw} – feedwater flow rate, [m^{3}s^{-1}]
q_s – generated steam mass-flow rate, [kgs^{-1}]
q_{sl} – steam leaks, [kg^{-1}]
q_w – required water flow rate, [m^3 per year]
$r_{0,4bar}$ – latent heat of evaporation at a pressure of 0.4 bar, [kJkg^{-1}]
SGC – unit costs of steam generation, [€ per tonne]
ΔT – flue gas temperature reduction, [°C]
TC – total steam generation costs, [€ per year]
TDS – total dissolved solids, [ppm]
TFS – total financial savings, [€ per year]
t – number of annual operating hours of the steam boiler plant, [hour per year]
t_c – condensate temperature, [°C]
t_{fg} – temperature of the exhaust flue gases, [°C]
t_{fw} – feedwater temperature, [°C]
t_{mu} – make-up water temperature, [°C]
WS – water cost savings needed to replace irreversible condensate, [€ per year]

WTS – cost savings for wastewater treatment, [€ per year]
x_b – boiler blowdown rate, [%]
x_c – condensate returned as feedwater, [%]
x_{fs} – percentage share of flash steam generated during blowdown in total blowdown, [%]

Greek symbols

η – overall boiler efficiency, [%]
η_c – combustion efficiency, [%]
κ – conductivity of water, [μScm^{-1}]
κ_{bw} – conductivity of the boiler water, [μScm^{-1}]
κ_{fw} – feedwater conductivity, [μScm^{-1}]

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