FULL PAPER

A HOLISTIC APPROACH FORTHE OPTIMISATION OF INDUSTRIAL CO-GENERATION PLANTS

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Abstract

With the global trend moving towards the phasing out of fossil fuels, which are commonly used as a supplementary fuel in the sugar industry, comes the need for increasing the overall efficiency of co-generation plants. An increase in efficiency can result in a reduction in fuel consumption and increase in power generation. This study investigates the overall plant efficiency and operational capabilities of a co-generation plant to maximise the generation of electricity at a sugar mill. The sugar mill has a power purchase agreement in place with the local electrical utility, primarily during the off-crop season, when coal is utilised as a fuel source. As part of the agreement, the plant is contractually obliged to meet certain efficiency targets. The entire system, including the boilers, turbines, condensers and the pre-boiler setup, was modelled numerically and correlated with actual plant data. Multiple recommendations from a recent boiler inspection and operational audit were evaluated by using the numerical model, which would result in a 15% increase in the plant power-to-fuel ratio, if it were implemented. It was also used to evaluate the effects of various cost-effective modifications to the co-generation plant. This study underscores the significance of advanced simulation tools in enhancing the operational understanding and efficiency of complex power-generation systems.

Keywords: co-generation, power plant, energy efficiency, boilers, turbines, numerical process modelling

Introduction

The transition away from fossil fuels has prompted industries worldwide to reassess their energy production methods. In sectors such as sugar production, which has traditionally relied on fossil fuels for supplementary power generation, optimising co-generation plants becomes critical for its sustainability and economic viability. Co-generation plants offer the dual benefit of generating electricity while utilising process heat, but their efficiency is reliant upon various factors, including the equipment design, operational practices and fuel sources (Cengel and Boles, 2015).

This paper focuses on a case study conducted at a sugar mill equipped with a co-generation plant consisting of two boilers each, with a condensing turbine-alternator set. Operating under a power purchase agreement with the local electrical utility, the plant aims to maximise electricity generation, while minimising fuel consumption.

The relevance of power purchase agreements underscores the economic considerations that drive efficiency enhancements in co-generation plants. These agreements provide a framework for the sale of electricity generated by the plant to the local utility, which incentivises plant operators to maximise the output, while minimising the costs. Thus, the optimisation efforts outlined in this paper contribute not only to environmental sustainability, but they also align with the economic imperatives, ensuring the long-term viability of co-generation plants in the transition towards renewable energy sources.

To achieve this goal, the study employs advanced numerical modelling techniques to simulate the entire co-generation plant, by integrating both boilers, both turbine-alternator sets, the various condensers, as well as the steam demand from the factory (when applicable).

As a result, the developed numerical model was utilised to assess the impacts of certain recommendations that were made from a recent boiler inspection and operational audit, which can maximise the power-to-fuel ratio when burning coal during the off-crop season, as the plant is contractually obliged to provide power at an overall efficiency of 1.4 MWh/ton of coal. Since coal is an imported commodity at the site, and it is used as the primary fuel source during the off-crop season to generate electricity for the local grid, it is crucial to maximise the amount of electrical power that is generated per ton of coal burnt.

Methodology and Modelling Approach

This study makes use of the integrated boiler process modelling methodology to model the co-generation plant that was investigated in this study. The methodology accounts for the following:

- the solution of the fundamental balance equations (mass, energy and momentum);
- the analysis of the performance characteristics of individual components, including the heat transfer rate, the work rate and pressure changes;
- the incorporation of fluid property relationships that are specific to the system being studied; and
- the specification of boundary values at the inlet and/or outlet.

In the context of the overall plant and boiler analysis, Rousseau *et al*. (2023) illustrated that the generic set of balance equations can be simplified as follows:

$$\sum \dot{m}_i = \sum \dot{m}_e$$

$$\sum \dot{m}_i(h_i) + \dot{Q} = \sum \dot{m}_e(h_e)$$

$$p_i + \Delta p_M = p_e + \Delta p_L \tag{1}$$

In Equation 1, $\dot{m}$ is the mass flow rate, h is the static enthalpy, p is the static pressure, $\dot{Q}$ is the rate of heat transfer to the fluid, Δp_M is the total pressure rise due to machine work, and Δp_L is the total pressure loss. Note that the subscripts *i* and *e* define the inlet and exit conditions, respectively.

In Figure 1, a generalised process flow diagram of an industrial sugar mill plant is presented. The main component is the boiler, where solid fuel (i.e. bagasse or coal) is mixed/entrained with air (primary, under-grate and secondary) and combusted in the Furnace (FUR). The chemical reactions that occur release a large amount of thermal energy, which is mainly transferred to the working fluid in the furnace waterwalls, Superheaters (SH1 and SH2), Main Bank (MB) and Economisers (EC), in order to generate steam. This steam is utilised as process steam for factory applications, prior to which it is generally expanded through a turbine-alternator system to produce electricity for the plant. Any steam that is not required for process is allowed to expand further, is condensed in a condenser and returned to the cycle via the pre-boiler setup (which includes the deaerator, make-up water and hot well tanks). To increase the thermal efficiency of the process, the heat recovery tower would typically include Air Heaters (AH1 and AH2), which are used to preheat the combustion air.

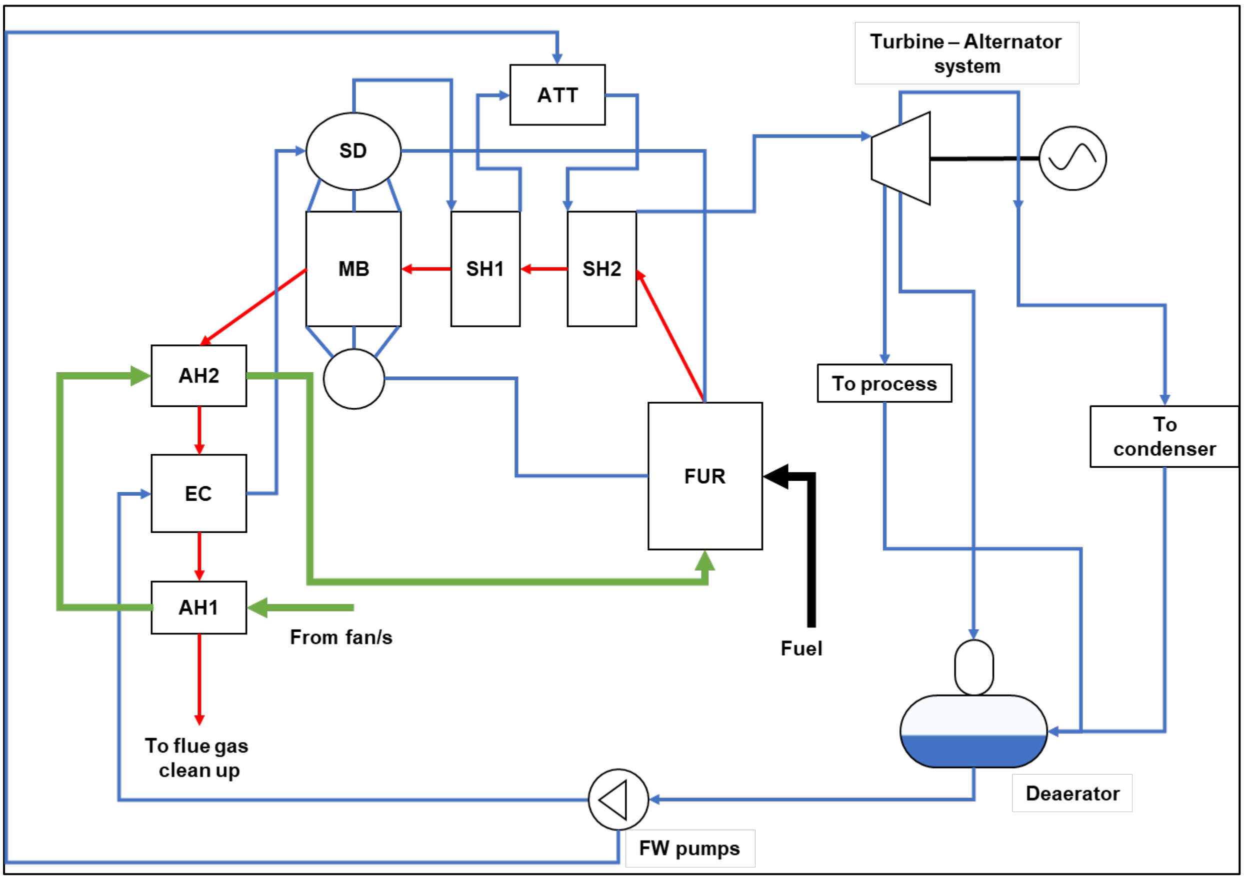

Figure 1. Generalised process flow diagram of an industrial sugar mill plant. Note: SD refers to the Steam Drum, ATT refers to the Attemperator, FW refers to Feedwater and TA refers to the Turbine Alternator set

It was beneficial to include the Balance of Plant (BOP) components (i.e. the condenser, turbine-generator, deaerator, etc.) in the model, which allowed for the investigation into how the boiler operation affects the overall plant efficiency and net electricity generation, which were the key variables that this study focused on improving.

Furnace modelling

The furnace is a critical component of the boiler system, thus it is essential that it is modelled with sufficient accuracy. The current study makes use of the projected method to capture the furnace heat transfer. The projected method (Rousseau *et al*., 2023), otherwise known as the Gurvich/Blokh method (Blokh, 1988), is a semi-empirical zero-dimensional model which assumes that all the physical quantities are uniform and that the results are averaged over the heating surfaces. Despite this, it is extensively applied in industry and in academia for the analysis and design of boilers (Rousseau *et al*., 2023).

Zero-dimensional models operate under the assumption that heat transfer within the furnace is primarily governed by radiation ($\dot{Q}_{rad}$) and that the furnace comprises a singular, uniform participating medium that emits radiation towards a solitary isothermal surface, notwithstanding the potential presence of multiple surfaces at varying temperatures. Consequently, a single equation is utilised to estimate the overall rate of radiant heat projected from the radiating gas volume to the surrounding surfaces. Subsequently, distinct portions of this total radiation are assigned to different surfaces within the furnace, encompassing elements such as the water walls, refractory walls and the furnace exit plane. The interested reader is directed to the works of Rousseau *et al*. (2023) and Blokh (1988) for further information relating to the detailed formulations of the projected method.

Heat exchanger modelling

The exiting flue gas will continue its path from the furnace through the remaining heat exchangers, as illustrated in Figure 1. All the downstream heat exchangers (SH2 through to AH1) are fundamentally modelled as tube banks with unique geometrical properties. The total heat transfer $\dot{Q}$ through any heat exchanger can be calculated as follows (Cengel and Boles, 2015):

$$\dot{\mathrm{Q}} = UA\Delta T_{LM} \tag{2}$$

where U is the overall heat transfer coefficient, A is the total heat transfer surface area, and ΔT_{LM} is the Logarithmic Mean Temperature Difference (LMTD) between the two fluids.

Figure 2 illustrates the typical input and output nodes that each heat exchanger component requires. Note that the furnace direct radiation component ($\dot{Q}_{furnace\ direct\ rad,i}$) includes the luminous direct radiation component emitted from the hot gases within the furnace. A portion of the direct radiation will bypass ($\dot{Q}_{bypass,\ rad,i}$) the heat exchanger element and radiate to the downstream heat exchanger component. For heat exchangers downstream of the primary superheater (SH1), the bypass radiation component is negligible.

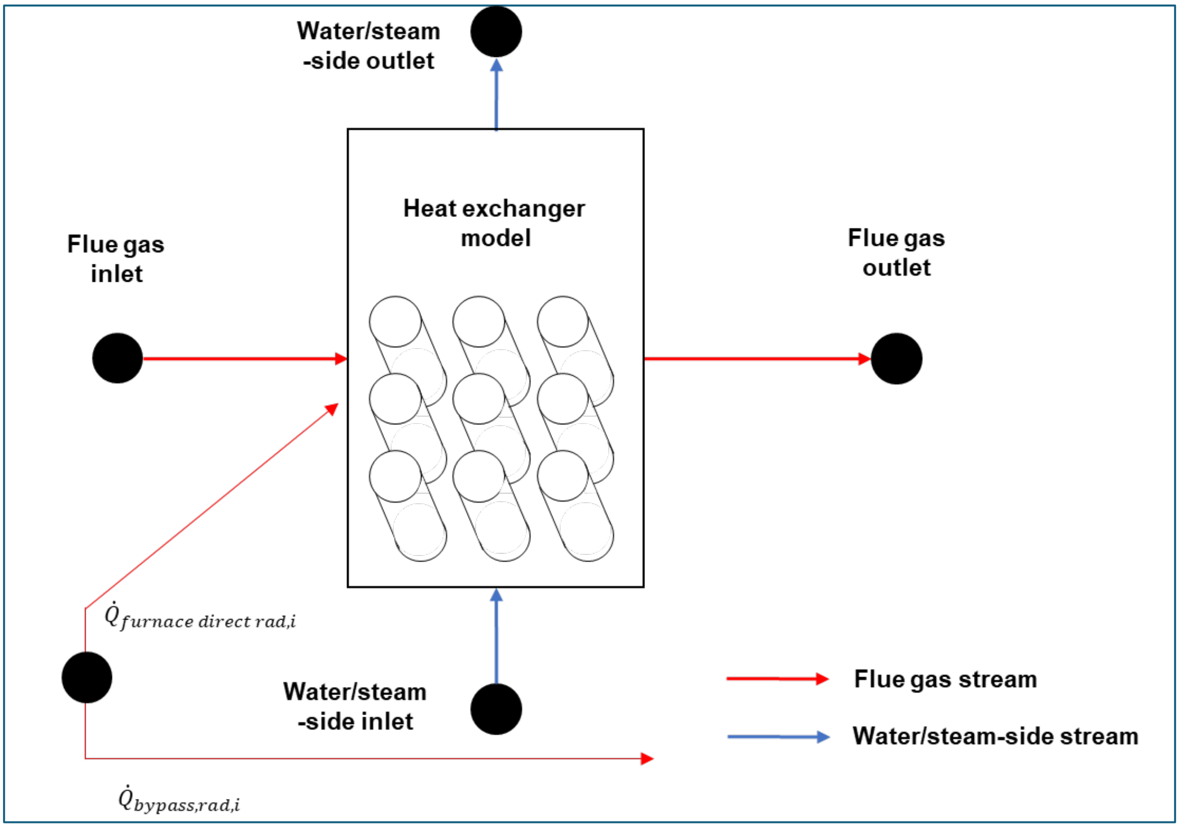

Figure 2. Schematic of a generic flue gas to water/steam tube bank heat exchanger model

Air Heaters 1 and 2 (AH1 and AH2) utilised the same configuration, the only difference being that the air would be the working fluid and flows over the tube bank tubes, whilst the flue gas would be directed through the tubes.

The theoretical models for the internal and external heat transfer coefficients, which are included in the overall heat transfer coefficient (U) of Equation 2, utilised the Gnielinski (1976; 2010) and Zukauskas (1972) approaches for convective heat transfer. These models and simplifying assumptions specific to particle laden flows are formulated in the VDI Heat Atlas (VDI Heat Atlas, 2010).

Balance of plant modelling approach

The modelling of the various BOP components makes use of the mass, energy and momentum equations given in Equation 1. An important BOP component is the steam turbine, which converts the enthalpy of steam into mechanical energy. The turbine model calculates the enthalpy after the turbine for multiple stages, using the inlet enthalpy, isentropic efficiency and nominal values. The mechanical power that is generated is then sent to the generator model. The initial tuning was conducted by using the available site data to determine the respective isentropic efficiencies. The isentropic efficiency defined by Sayers (1990) was utilised for the various turbomachinery components found in the BOP system.

As demonstrated by Alobaid *et al*. (2017), all the BOP components are essential process components that are necessary to capture the overall thermal efficiency of thermal power and co-generation plants.

Numerical model tuning

As with the BOP components, valuable site data was made available for the development and tuning of the numerical model. The initial numerical model was developed by using the original plant layout drawings, as well as previous reports, to obtain an accurate geometric representation, which was required to sufficiently model components such as the heat exchangers, the furnace and the BOP components. This initial model was tuned by using the commissioning data, which was achieved by using fouling factors to match the steam and flue gas conditions through the heat exchangers, by using the non-uniformity factor in the furnace model to estimate the correct exit furnace temperature, as well as by using the unburnt fuel factor and excess air controls to account for the flue gas properties after the main bank. As a result, the initial model was able to produce results within 5% of the commissioning data.

Having a verified numerical model of the plant in its commissioned/as-designed state, the current operational site data were then used to tune the model, using the same process as described above. This resulted in a further adjustment of the various factors. Figure 3 illustrates the numerical models' predictions of the exit flue gas temperature versus the site data measurements for discrete steaming loads centred around the 100% Maximum Continuous Rating (MCR) for Boiler 1.

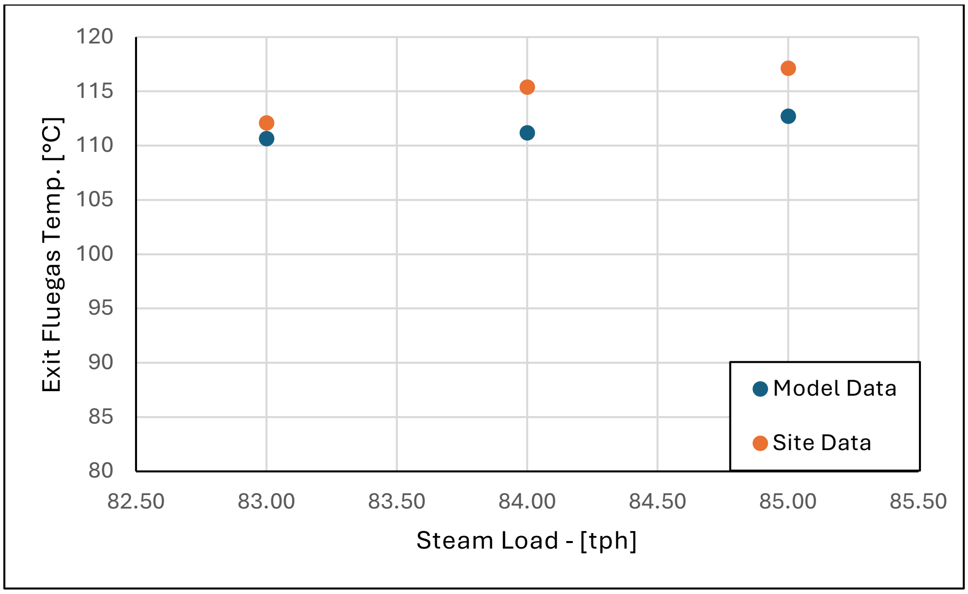

Figure 3. Exit flue gas temperature versus steaming load comparison between the model predictions and available site data

The numerical model tuning was an iterative process and resulted in a numerical model that could approximately predict the necessary process variable required for the investigation into the various plant improvement recommendations stemming from the operational audit that was conducted at the site.

Results and Discussion

Plant description

The plant under investigation is located in southern Africa and consists of two typical bi-drum water tube boilers, operating at 45 bar(g) and producing superheated steam at a temperature of 440°C. Boiler 1 has a capacity of 110 tph on bagasse and 90 tph when firing coal, and it is connected to a 21.7 MWe condensing turbine alternating set, while Boiler 2 has a capacity of 100 tph on bagasse and 80 tph on coal and is connected to an 18.8 MWe condensing turbine alternating set. As part of the power purchase agreement, the plant is contractually obliged to supply electricity to the local power utility at an overall efficiency of 1,4 MWh/ton of coal.

The recommendations for the improvement of each boiler, primarily for coal firing, can be summarised as follows:

Boiler 1:

A1. Reinstate the plugged superheater elements and replace refractory in the furnace.

A2. Increase the under-grate air temperature using the bleed steam from Boiler 2 to operate an existing steam air heater that is typically bypassed.

A3. Reduce the final dry oxygen content via excess air control.

Boiler 2:

B1. Reduce the final dry oxygen content via excess air control.

The effects of implementing these changes were modelled by using the developed thermal model. The numerical results are presented in the following section:

Fuel specifications

The operating coal specification is provided in Table 1. The fuel specifications were obtained from fuel samples taken from the site and are an important input parameter into the combined model, since this would dictate the amount of energy available to the boilers and it would provide an insight into the ash and emissions exiting the system.

Table 1. Coal ultimate analysis

Fuel Constituent	**Value**	**Unit**
Carbon	68.08	%
Hydrogen	3.62	%
Nitrogen	1.65	%
Oxygen	8.43	%
Sulphur	0.37	%
Ash	15.20	%
Inherent moisture	2.65	%
Fuel energy content	**Value**	**Unit**
Higher heating value	26.66	MJ/kg

Numerical results

In this study, the electrical power-to-coal consumption is a useful variable to report, as it illustrates the overall thermal efficiency of the system in a simple and eloquent manner. Table 2 below highlights the base case, or current operational status, of Boilers 1 and 2, respectively.

Table 2. The current operational performance of Boiler 1 and Boiler 2

	Steam load [tph]	SH exit Temp. [ºC]	AH Outlet Temp. [ºC]	Coal load [tph]	Power-to-fuel [MWh/T]
Boiler 1	84	420	114	11.2	1.33
Boiler 2	72	438	147	9.6	1.41

It can be seen that Boiler 1 was not able to achieve the exit steam temperature of ±440°C, which affected the downstream components in the process, namely the turbine. This is the driving factor as to why the plant cannot reach the contractual power-to-coal consumption of 1.4 MWh/ton. In addition, a lower under-grate air temperature was recorded, which can lead to a reduced combustion efficiency in the furnace.

Table 3 below outlines a selection of the immediate Boiler 1 recommendations, namely, from A1 through to A3. The numerical results show that a 2% increase in the power-to-coal consumption is achievable when acting on the recommendations, especially when considering the exit steam temperature, of which the SH area increase plays a significant role in achieving the desired steam conditions. The AH refurbishment recommendation (A2) would only be achievable if Boiler 2 is burning bagasse. Since Boiler 1 uses a steam air heater, more steam would be available from Boiler 2 to achieve a more stable under-grate temperature, while providing sufficient power.

Table 3. The overall system improvement of Boiler 1, based on various recommendations at constant MCR steam loads

Recommendation	Steam load [tph]	SH exit Temp. [ºC]	AH Outlet Temp. [ºC]	Coal load [tph]	Power-to-fuel [MWh/T]
A1 – SH area increase only	84	435	114	11.3	1.38
A1 – Refractory included only	84	425	114	11.2	1.38
A2 - AH Refurbishment only	84	421	130	11.1	1.41
A3 - Reduce final gas O2 dry volume to 7.57% (excess air 50%)	84	418	114	10.9	1.41
Above recommendations implemented	84	439	130	11.1	1.40
*Condenser improved performance	84	420	114	11.2	1.55

In addition to the immediate recommendations, the performance of the condenser was incorporated in Table 3, which illustrates another factor that can improve the power-to-coal consumption of the overall plant. At present, the condenser is operating sub-optimally, which results in the higher back-pressure seen in the turbine.

Implementing recommendations A1 through to A3 can result in Boiler 1 being able to achieve the exit steam conditions, along with a 1.5% increase in the power-to-fuel consumption ratio.

However, the largest increase in the power-to-fuel ratio (approximately 15%) is realised when the condenser performance is improved in Boiler 1. This can be achieved practically by an operational performance review of the condenser and improved maintenance protocols. Note that for the case with the improved condenser performance, the exit steam temperature was not met (refer to Table 3), since the simulation was performed without all the prior recommendations being implemented together.

Boiler 2 required fewer recommendations, in order to achieve favourable results. Table 4 showcases the results by reducing the dry O_2 volume percentage after the main bank.

Table 4. The overall system improvement of Boiler 2, based on excess air control

	Steam load [tph]	**SH exit Temp. [ºC]**	**AH Outlet Temp. [ºC]**	**Coal load [tph]**	**Power-to-fuel [MWh/T]**
B1 - Reduce final gas O2 dry volume to 7.64% (excess air 51%)	72	436	147	9.6	1.56

In order to achieve effective ways of practically reducing the final dry O_2 percentage, the following can be controlled or improved in the boiler operation:

1. Adjusting the air-to-fuel ratio and controlling the excess air can lead to more efficient combustion, especially for solid fuel combustion.
2. The refurbishment and maintenance of air heaters, part of which includes inspecting the air heaters and back-end ducting for leakages. Air heaters preheat the combustion air, which enhances the combustion stability by using hot air and aids in reducing unburnt fuel particles, which results in a high combustion efficiency.

As stated previously, the primary objective was to assess the impact of various operational and maintenance recommendations on the entire plant, in order to maximise the power-to-fuel ratio when burning coal. By implementing the recommendations of A1 to A3 and B1 for Boilers 1 and 2, the power-to-fuel consumption ratio of the entire plant can be increased by approximately 2.7%. Furthermore, if one includes condenser improvements to the recommendations for Boiler 1 (as presented in Table 3), an approximate 10% increase of the power-to-coal ratio can be realised, which would enable the plant to reach its contractual obligations when both boilers are in operation.

Conclusion

In conclusion, this paper has presented a comprehensive analysis of a co-generation plant in a sugar mill setting, focusing on two boilers operating under a power purchase agreement with the local utility. The transition away from fossil fuels has necessitated a re-evaluation of energy production methods, which makes the optimisation of co-generation plants crucial for their sustainability and economic viability.

By using advanced numerical modelling techniques, the study effectively simulated the entire plant system, integrating the boilers, turbines, condensers and steam demand from the factory, when applicable. This modelling approach allowed for the quantification of various recommendations derived from recent boiler inspections and operational audits. The numerical model enabled the assessment of the impacts of the proposed recommendations to maximise the electricity-to-fuel ratio when burning coal during the off-crop season to supply the local electrical grid. Notably, the study identified key areas for improvement, both in Boiler 1 and Boiler 2, with the condenser system for Boiler 1 being a specific area that was identified to increase the power-to-fuel consumption ratio by as much as 15%, which would enable the plant to achieve the 1.4 MW of electricity per ton of coal, as required by the power purchase agreement that is currently in place.

In essence, this study demonstrates the role advanced numerical modelling has in showcasing the effects various recommendations that are made after a boiler inspection and an operational audit are conducted have on the overall plant efficiency. Furthermore, this model can be used to substantiate the capital expenditure for the improved maintenance and operation of similar plants.

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