Performance evaluation of high-ratio biomass co-firing with low-rank coal in a 100 MWe circulating fluidized bed power plant

Rico Rian Avero[1], *Hifni* Mukhtar Ariyadi[1*], *Anthony* Nathaniel[1], *Fauzun*[1], *Indro* Pranoto[1], *Muhammad* Agung Bramantya[1]

[1]Department of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia

Abstract. Biomass co-firing has emerged as a practical approach for reducing fossil-based emissions in coal-fired power plants while utilizing existing infrastructure. This study evaluates high-ratio biomass co-firing up to 80% using woodchip in a 100 MW Circulating Fluidized Bed (CFB) power plant. The analysis was performed using GateCycle simulation under full-load operating conditions, covering thermodynamic, environmental, and economic aspects. The results show that increasing biomass fraction leads to higher fuel consumption, higher auxiliary power demand, and increased boiler heat losses, resulting in gradual reductions in boiler and plant efficiency due to the lower heating value and higher moisture content of biomass fuel. On the other hand, biomass co-firing significantly reduces specific CO_2 emissions from approximately 1050 kg/MWh to around 280 kg/MWh at 80% co-firing, while SO_2 emissions also decrease due to the lower sulfur content of biomass. Preliminary slagging and fouling assessment indicate that higher biomass fractions increase ash deposition tendency inside the boiler. The preliminary economic evaluation suggests that biomass co-firing remains economically feasible under the investigated operating conditions. Overall, the use of woodchip as a co-firing fuel shows promising potential for supporting decarbonization in existing CFB power plants, although high biomass utilization may reduce thermal performance.

1 Introduction

The increasing demand for energy continues to strengthen the role of coal-fired power plants as a reliable source of large-scale electricity generation. However, their significant contribution to CO_2 emissions presents a major challenge for achieving global decarbonization targets, particularly in countries such as Indonesia where coal remains dominant in the energy mix [1].

Biomass co-firing has emerged as a practical and cost-effective solution to reduce emissions without requiring major modifications to existing infrastructure. This approach enables partial substitution of coal with renewable fuels while maintaining operational stability. Circulating Fluidized Bed (CFB) boilers provide excellent fuel flexibility and combustion stability, allowing the utilization of various biomass types and supporting relatively high biomass co-firing ratios compared to conventional combustion systems [2].

Recent studies have shown that biomass co-firing can significantly reduce fossil-derived CO_2 emissions as well as SO_2 and NO_x emissions due to the lower sulfur and nitrogen contents of biomass fuels [2, 3]. These environmental benefits are mainly attributed to the renewable nature of biomass and its lower sulfur and nitrogen content compared to coal. However, the use of biomass also introduces several limitations. Due to its lower calorific value and higher moisture content, biomass requires higher fuel consumption to maintain the same power output, which can reduce boiler thermal efficiency and increase heat losses during combustion.

In addition to thermodynamic limitations, biomass co-firing presents operational challenges such as slagging, fouling, and bed agglomeration, particularly in fluidized bed systems [4]. These issues can affect heat transfer performance and long-term system reliability, especially at higher co-firing ratios. The severity of these operational problems is strongly influenced by ash chemistry, particularly the presence of alkali compounds such as K_2O and Na_2O in biomass ash. Biomass fuels with high alkali content tend to promote the formation of low-melting ash compounds and sticky deposits on heat transfer surfaces, thereby increasing slagging and fouling tendencies [9]. Therefore, preliminary ash chemistry assessment is important to evaluate the operational feasibility of high-ratio biomass co-firing in CFB systems.

Large-scale biomass co-firing implementation depends on biomass availability, logistics, seasonal variation, storage condition, and fuel moisture characteristics. In practice, most existing co-firing systems still operate at relatively low biomass fractions due to supply chain limitations. However, Indonesia has significant biomass potential, including approximately 1300 MW in West Sumatra according to the RUPTL PLN 2025–2034 report [8].

Despite extensive research, most previous studies focus on low biomass fractions or simplified modeling approaches. As a result, there is still limited understanding of the performance of high biomass co-firing under real operating conditions, particularly in industrial-scale power plants [5-7].

* Corresponding author: hifni.m.a@ugm.ac.id

Therefore, this study evaluates the performance of biomass co-firing up to 80% using woodchip in a 100 MW Circulating Fluidized Bed (CFB) power plant, based on operational data from the Teluk Sirih power plant, Indonesia. The analysis is conducted using GateCycle simulation across co-firing ratios from 0% to 80% under full-load conditions. The evaluation focuses on energy performance and environmental impact, particularly in terms of boiler efficiency and emission characteristics.

This study is based on real operational data and examines the behavior of high biomass co-firing in a CFB power plant. It highlights how biomass utilization affects energy performance and emission characteristics, providing practical insights that can support the implementation of co-firing strategies in similar systems.

2 Materials and methods

2.1 Materials and measurements

This study is conducted on a 100 MW Circulating Fluidized Bed (CFB) coal-fired power plant located in Teluk Sirih, Indonesia. The system operates based on a conventional Rankine cycle consisting of a boiler, steam turbine, condenser, and feedwater heating system. The analysis is based on real operational data.

The characteristics of fuels used in this study are summarized in Table 1. The primary fuel is low-rank coal, which represents the actual fuel used in the Teluk Sirih power plant. Biomass in the form of woodchip is introduced as a secondary fuel for co-firing scenarios. The fuel properties used in this study are based on laboratory testing results under the as received (Ar) basis, which reflects the actual condition of fuel as supplied to the power plant.

Table 1. Main characteristics of coal and biomass.

Parameter	Coal	Biomass
Moisture (wt%)	32.89	34.2
Ash content (wt%)	5.97	1.57
Volatile matter (wt%)	31.96	53.72
Fixed carbon (wt%)	29.18	10.50
Sulfur (wt%)	0.25	0.11
Gross calorific value (Kcal/kg)	4209	3045
Carbon (wt%)	44.08	31.23
Hydrogen (wt%)	3.33	3.86
Nitrogen (wt%)	1.18	0.33
Oxygen (wt%)	12.30	28.73

In addition to proximate and ultimate fuel properties presented in Table 1, ash chemistry characteristics were also evaluated because ash composition significantly influences slagging, fouling, and bed agglomeration behavior in CFB boilers. Therefore, the ash composition and ash fusion temperature data summarized in Table 2 were analyzed to provide a preliminary assessment of ash-related operational risks during biomass co-firing. The data were obtained from laboratory testing conducted during the existing biomass co-firing at the Teluk Sirih power plant [12].

Table 2. Ash composition and ash fusion temperature of coal and biomass.

Component	Coal	Biomass
SiO_2 (wt%)	46.70	17.31
Al_2O_3 (wt%)	26.04	8.72
Fe_2O_3 (wt%)	4.85	5.32
CaO (wt%)	6.83	37.87
MgO (wt%)	3.68	11.40
Na_2O (wt%)	2.92	0.86
K_2O (wt%)	0.52	10.30
TiO_2 (wt%)	0.59	0.32
SO_3 (wt%)	7.29	3.46
Cl (wt%)	0.03	0.13
Ash Fusion Temperature Initial Deformation (°C)	1210	1270
Ash Fusion Temperature Softening (°C)	1270	1280
Ash Fusion Temperature Hemispherical (°C)	1290	1300
Ash Fusion Temperature Initial Fluid (°C)	1320	1330

The ash analysis indicates that woodchip biomass contains higher CaO and K_2O contents compared to coal, which may increase alkali-related deposition tendency at elevated biomass fractions. However, both coal and biomass exhibit relatively high ash fusion temperatures compared to the normal CFB furnace operating temperature (850–950 °C) [10], indicating relatively low risk of severe ash melting and bed agglomeration under the investigated operating conditions.

2.2 Process description

An existing 100 MW Circulating Fluidized Bed (CFB) coal-fired power plant located at Teluk Sirih, Indonesia, was selected as the basis for process simulation of biomass co-firing. The simulation aims to evaluate plant performance under varying biomass fractions using actual operational conditions. The overall process flow diagram of the system is presented in Fig. 1.

The fuel handling process begins at the coal yard, where low-rank coal is stored prior to combustion. In the co-firing scenario, biomass in the form of woodchip is directly blended with coal using heavy equipment before being transported to the bunker. This method ensures a relatively uniform fuel mixture and represents a practical approach widely adopted in existing power plants, as it allows biomass utilization without significant modification to the fuel feeding system [6].

The fuel mixture was combusted inside the CFB boiler under fluidized bed conditions. The generated flue gas passed through heat exchange surfaces, including economizer, evaporator, and superheater, before entering the electrostatic precipitator (ESP) and stack. The water-steam system operated based on a conventional Rankine cycle consisting of boiler, steam turbine, condenser, feedwater heaters, and pumps. Variations in biomass fraction affect combustion temperature, flue gas characteristics, steam generation, and overall plant efficiency.

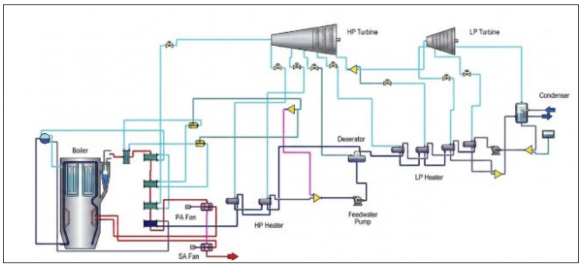

Fig. 1. The entire process flow diagram of Teluk Sirih power plant.

2.3 Methodology

This study was conducted using GateCycle software based on commissioning data, operational parameters, fuel characteristics, and heat balance data from the Teluk Sirih power plant. The developed thermodynamic model represents the complete Rankine cycle system, including boiler, steam turbine, condenser, and feedwater heating system. Model validation was performed by comparing simulation results with actual operating data, including steam flow rate, steam pressure, steam temperature, and flue gas temperature. After validation, off-design simulations were conducted for biomass co-firing ratios from 0% to 80% under full-load operating conditions.

After validation, the model is converted into off-design mode to simulate various operating conditions. Biomass co-firing scenarios are introduced by varying the biomass fraction from 0% to 80%. During all simulations, the overall AFR was maintained relatively constant to represent stable full-load operation and evaluate general thermodynamic trends under controlled conditions. However, actual biomass combustion may require adjustment of primary and secondary air distribution due to differences in volatile release and combustion characteristics.

The performance evaluation focuses on energy, environmental, and preliminary economic performance under various biomass co-firing ratios. In addition to thermodynamic and environmental evaluation, preliminary slagging and fouling assessments were conducted to evaluate the potential operational impact of biomass co-firing on the CFB boiler. The assessment was performed using ash chemistry analysis based on laboratory-tested ash composition data of coal and woodchip biomass. The slagging tendency was estimated using the Base-to-Acid ratio (B/A) as presented in Equation (1), while the fouling tendency was evaluated using the Fouling Index (Fu) as presented in Equation (2), following the method proposed by Lachman et al. [9].

$$B/A=(Fe_2O_3+CaO+MgO+Na_2O+K_2O)/((SiO_2+Al_2O_3+TiO_2)) \quad (1)$$

$$Fu=B/A\times(Na_2O+K_2O) \quad (2)$$

Based on the slagging classification criteria, B/A values lower than 0.5 indicate low slagging tendency, values between 0.5–1.0 indicate medium slagging tendency, and values higher than 1.0 indicate high slagging tendency.

Meanwhile, based on the fouling classification criteria, Fu values lower than 0.6 indicate low fouling tendency, values between 0.6–40 indicate medium fouling tendency, and values higher than 40 indicate high fouling tendency.

Boiler efficiency is calculated using the indirect (heat loss) method, which considers major heat losses during the combustion process. The boiler efficiency was calculated by the following equation (3) to (7).

$$\eta_b=1-(HL_1+HL_2+HL_3+HL_4+HL_5) \quad (3)$$

$$HL_1=W_g\times(h_{fg}-h_{air})/HHV_{AR} \quad (4)$$

$$HL_2=TM\times(h_v-h_a)/HHV_{AR} \quad (5)$$

$$HL_3=9\times H_2\times(h_v-h_a)/HHV_{AR} \quad (6)$$

$$HL_4=HHV_{ubc}\times C_{ub}/HHV_{AR} \quad (7)$$

HL1, HL2, HL3, HL4, and HL5 represent heat losses due to dry flue gas, fuel moisture, hydrogen combustion, unburnt carbon, and radiation losses, respectively. HL_5 is estimated based on the ABMA (American Boiler Manufacturers Association) standard chart. The overall plant performance is further evaluated using plant efficiency, which represents the ratio between net electrical power output and total fuel energy input. The plant efficiency considers the effect of increasing auxiliary power consumption during biomass co-firing operation (8).

$$\eta_{plant}=P_{net}/(m_{fuel}\times HHV) \quad (8)$$

Where η_{plant} is the overall plant efficiency, P_{net} is the net electrical power output, m_{fuel} is the total fuel mass flow rate, and HHV is the higher heating value of the fuel mixture.

In addition to boiler thermal performance, auxiliary power consumption was also evaluated to assess the operational impact of biomass co-firing on overall plant performance. The auxiliary load considered in this study consists of major 6 kV motor-driven equipment, including Primary Air Fan (PAF), Secondary Air Fan (SAF), Induced Draft Fan (IDF), Boiler Feed Pump (BFP), and Condensate Pump (CP).

The auxiliary power requirement was estimated based on the simulated increase in fuel flow rate, combustion air demand, and flue gas flow under different biomass co-firing ratios. Higher biomass fractions require larger fuel consumption due to the lower heating value and higher moisture content of biomass fuel, resulting in increased fan and pump power. The fan efficiency formulation is presented in Equation (9), while the volumetric flow rate formulation is presented in Equation (10). Thus, the actual fan shaft power formulation is presented in Equation (11), and the total auxiliary power consumption formulation is presented in Equation (12).

$$\eta = W_{ideal} / W_{actual} \quad (9)$$

$$Q = m / \rho \quad (10)$$

$$W_{shaft} = Q \Delta P / \eta_{fan} \quad (11)$$

$$P_{aux} = P_{paf} + P_{saf} + P_{idf} + P_{bfp} + P_{cp} \quad (12)$$

The emission evaluation in this study was conducted based on combustion stoichiometry and flue gas composition obtained from the GateCycle simulation results. The combustion process of fuel elements such as carbon, hydrogen, and sulfur can be represented by the following simplified reactions:

$$C + O_2 \rightarrow CO_2$$
$$H_2 + 1/2O_2 \rightarrow H_2O$$
$$S + O_2 \rightarrow SO_2$$

The overall combustion reaction for the fuel mixture can be expressed using the generalized stoichiometric equation as follows:

$$C_aH_bO_cS_e + \lambda x(O_2 + 3.76N_2) \rightarrow aCO_2 + b/2H_2O + eSO_2 + (\lambda - 1)xO_2 + 3.76\lambda xN_2$$

Where λ represents the excess air ratio, defined as the ratio between actual combustion air and stoichiometric air. The CO_2 and SO_2 emissions were estimated from the elemental composition of the fuel and the simulated flue gas composition under each biomass co-firing condition. CO_2 emissions were expressed as specific emissions (kg/MWh) based on net electrical output, while SO_2 emissions were expressed in mg/Nm^3. For biomass fuel, the released CO_2 was considered biogenic carbon emission following the carbon-neutral concept commonly applied in biomass energy systems. Therefore, increasing biomass fraction reduces the effective fossil-derived CO_2 emission intensity of the power plant.

A preliminary economic assessment was also conducted to evaluate the feasibility of biomass co-firing implementation under different biomass co-firing ratios. The analysis includes fuel cost, annual cash flow, Net Present Value (NPV), Internal Rate of Return (IRR), and payback period. The economic evaluation was performed using simplified operational assumptions based on constant electricity selling price and fixed operational cost assumptions. The electricity selling price was assumed to be 0.06 USD/kWh based on the current electricity tariff applied at the power plant. The Specific Fuel Consumption (SFC) was determined from the ratio between total annual fuel consumption and annual electricity production. Fuel cost was calculated based on coal-biomass fuel composition and fuel price, as expressed in Equation (13) and NPV expressed in Equation (14).

$$Fuel\ Cost = (1 - x_b) \times SFC \times P_{coal} + x_b \times SFC \times P_{biomass} \quad (13)$$

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_0 \quad (14)$$

where x_b is biomass fraction, SFC is specific fuel consumption, P_{coal} is coal price, $P_{biomass}$ is biomass price. CF_t is annual cash flow, r is discount rate, n is project lifetime, and I_o is the initial investment cost.

Finally, the results from all simulation scenarios are analyzed to identify performance trends and trade-offs between efficiencies, economic benefits, and emission reduction. Based on this comprehensive evaluation, the optimal biomass co-firing ratio is determined, considering both technical feasibility and practical implementation in a real CFB power plant. This methodology ensures that the study provides a robust and realistic assessment of biomass co-firing performance under various operating conditions.

3 Results and discussion

3.1 Model validation

The developed thermodynamic model was validated to ensure its capability in accurately representing the actual performance of the Teluk Sirih power plant. The validation process was conducted by comparing simulation results with commissioning data [11], as presented in Table 3. Key parameters used for validation include main steam flow rate, main steam temperature and pressure, flue gas temperature, and overall plant performance indicators.

The comparison shows that the deviation between simulation and actual data remains within an acceptable range, generally below ±7%. This level of agreement indicates that the model is sufficiently accurate to represent real operating conditions. Minor discrepancies may arise from simplifications in modeling assumptions, measurement uncertainties, and operational fluctuations during plant operation. Overall, the validation results indicate that the model is able to represent the plant performance with acceptable accuracy.

Table 3. Comparison of key parameters from simulation and commissioning data.

Parameter	Commissioning	Simulation	Deviation
Power (MW)	112	112.02	0.018%
Steam inlet flow (t/h)	410	411.5	0.367%
Steam inlet pressure (MPa)	8.83	8.79	-0.313%
Steam inlet temperature (°C)	535	534.55	-0.084%
Coal flow (t/h)	63.93	66.69	4.14%
Furnace out temperature (°C)	901	897	-0.446%
Flue gas temperature (°C)	133	142.46	6.64%

In addition to commissioning data, further validation was performed using experimental data from biomass co-firing tests conducted in collaboration with PT PLN Puslitbang in 2024 [12], as summarized in Table 4.

Table 4. Comparison of key parameters from simulation and performance testing.

Parameter	Testing (0%)	Simulation (0%)	Testing (5%)	Simulation (5%)
Power (MW)	97.03	97.3	99.4	98.1
Steam inlet pressure (MPa)	8.4	7.6	8.6	8.8
Steam inlet temperature (°C)	530.2	529.9	536	532.1
Coal flow (t/h)	60.3	64.9	64.1	66.1
Furnace out temperature (°C)	915	908.5	900	909
Flue gas temperature (°C)	134	142.1	138	142.4

3.2 Performance Evaluation

The performance evaluation was conducted to assess the impact of biomass co-firing on thermodynamic, environmental, and economic aspects of the power plant under various operating conditions. The analysis covers biomass fractions from 0% to 80% under 100 MW full-load conditions. The high biomass fractions investigated in this study were intended to evaluate the potential performance of the CFB system under future high biomass co-firing conditions. In current plant operation, biomass co-firing ratios of approximately 10–20% have already been implemented under stable operating conditions without significant additional investment. However, implementing higher biomass fractions may require more reliable biomass supply, larger storage capacity, better fuel quality control, and more complex logistics management due to seasonal availability and moisture variation.

The simulation results show a consistent relationship between biomass fraction and fuel consumption. As illustrated in Fig. 2, increasing the biomass ratio leads to a steady rise in total fuel flow. At full-load (100 MW), the fuel flow increases from 65051.09 kg/h at 0% biomass to 87930.25 kg/h at 80%. This trend is mainly attributed to the lower heating value of biomass compared to coal, which requires a higher mass input to maintain the same energy output.

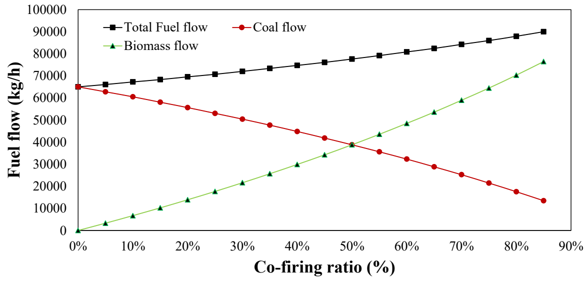

Fig. 2. Effect of biomass co-firing ratio on fuel flow distribution.

In line with the increase in fuel consumption, the boiler efficiency shows a gradual decline, as presented in Fig. 3. The boiler efficiency decreases from approximately 81.2% at 0% biomass fraction to around 78.6% at 80% co-firing. This reduction is primarily associated with the higher moisture content and lower calorific value of biomass, which increase latent heat loss and reduce effective heat absorption during combustion.

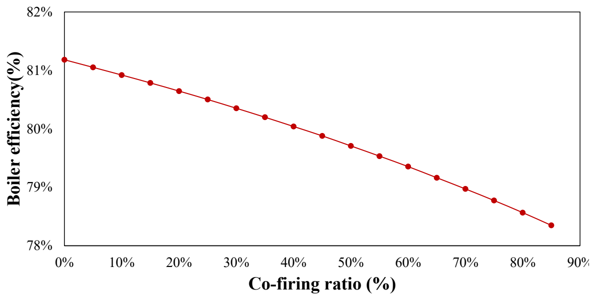

Fig. 3. Effect of biomass co-firing ratio on boiler efficiency.

The variation of boiler heat losses under different biomass co-firing ratios is presented in Fig. 4. Based on the indirect boiler efficiency method, HL1 represents heat loss due to dry flue gas, HL2 represents heat loss due to moisture contained in the fuel, HL3 represents heat loss due to H_2O formed from hydrogen combustion, HL4 represents heat loss due to combustible material in bottom ash and fly ash, and HL5 represents radiation and unaccounted heat losses.

The results indicate that HL2 and HL3 gradually increase with increasing biomass fraction due to the higher moisture and hydrogen contents of woodchip biomass. The increase in these losses contributes significantly to the reduction in boiler efficiency at elevated biomass ratios.

Meanwhile, HL1 also shows a slight increase because higher biomass fractions require greater total fuel consumption to maintain the same boiler load due to the lower calorific value of biomass. Consequently, the flue gas flow rate increases, leading to higher sensible heat loss carried by the exhaust gas.

In contrast, HL4 gradually decreases with increasing biomass fraction, indicating lower combustible loss in ash under the investigated operating conditions. In addition, HL5 remains relatively constant because radiation and external heat losses are assumed to be relatively stable during operation. Overall, the results suggest that the efficiency reduction at higher biomass fractions is mainly dominated by moisture-related heat losses and increased dry flue gas losses rather than incomplete combustion losses.

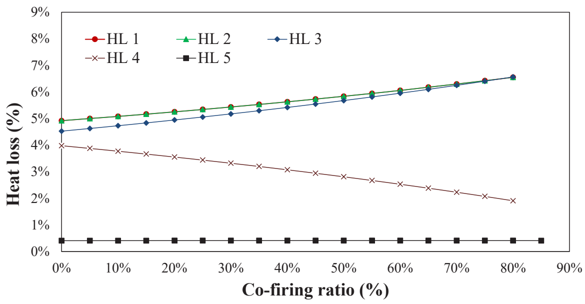

Fig. 4. Boiler heat losses at different co-firing ratios.

In addition to reducing boiler efficiency, higher biomass co-firing ratios also increase auxiliary power consumption due to the higher fuel flow requirement and increased combustion air demand associated with biomass combustion.

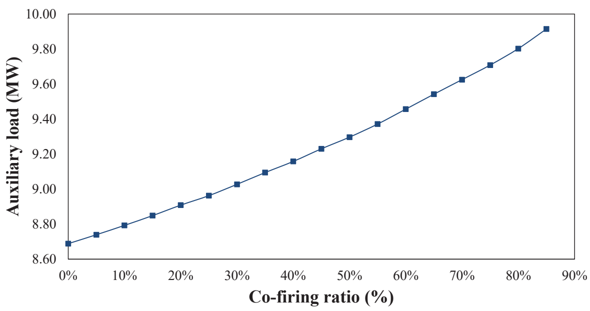

Fig. 5. Effect of biomass co-firing ratio on auxiliary power consumption.

As shown in Fig. 5, the total auxiliary power consumption gradually increases from approximately 8.7 MW at 0% co-firing to around 9.8 MW at 80% co-firing. This increase is primarily associated with the higher fuel consumption required to maintain the same boiler load due to the lower calorific value and higher moisture content of biomass fuel.

The increase in auxiliary load is mainly contributed by higher power consumption of major motor-driven equipment, including Primary Air Fan (PAF), Secondary Air Fan (SAF), Induced Draft Fan (IDF), Boiler Feed Pump (BFP), and Condensate Pump (CP). Higher biomass fractions require greater air flow and flue gas handling capacity, resulting in increased fan and pump power consumption.

In addition, the higher moisture content of biomass may reduce furnace temperature and increase latent heat loss, which further contributes to higher combustion air demand and reduced overall plant efficiency, as shown in Fig. 6.

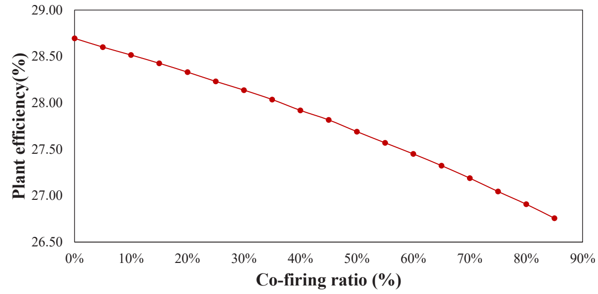

Fig. 6. Effect of biomass co-firing ratio on plant efficiency.

Despite the thermodynamic penalty, the environmental performance improves significantly with increasing biomass co-firing ratio. As shown in Fig. 7, both CO_2 and SO_2 emissions gradually decrease as the biomass fraction increases. The specific CO_2 emission decreases substantially from approximately 1050 kg/MWh at 0% co-firing to around 280 kg/MWh at 80% co-firing. This reduction is mainly associated with the carbon-neutral characteristic of biomass, where the CO_2 released during combustion is considered part of the short-term biogenic carbon cycle, thereby reducing the effective fossil-derived CO_2 emission intensity of the power plant.

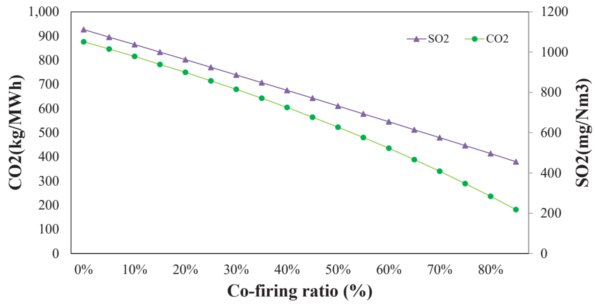

Fig. 7. Effect of biomass co-firing ratio on CO_2 and SO_2 emission.

Similarly, SO_2 emissions decrease from approximately 920 mg/Nm³ to around 400 mg/Nm³ as the biomass fraction increases. This trend is primarily attributed to the significantly lower sulfur content of woodchip biomass compared to coal.

In addition, lower furnace temperatures caused by higher biomass moisture content and lower calorific value may contribute to lower thermal NO_x formation tendencies. Nevertheless, NO_x formation in practical biomass co-firing systems is strongly influenced by combustion staging, excess air distribution, volatile release behavior, and local furnace temperature distribution. Therefore, the emission trends presented in this study should be interpreted as preliminary system-level indications under controlled operating assumptions. Detailed investigation of particulate matter (PM), unburnt carbon, CO emissions, and ash particle characteristics was beyond the scope of the present study. Further experimental measurements and CFDbased combustion analyses are recommended for future investigations.

Besides thermodynamic and environmental performance, biomass co-firing may also influence ash deposition behavior inside the boiler. Therefore, a preliminary slagging and fouling assessment was conducted based on ash chemistry analysis to evaluate the potential operational impact of increasing biomass fraction on the CFB system, as summarized in Table 5.

Table 5. Estimated slagging and fouling tendency under various biomass co-firing ratios.

Ratio (%)	B/A Ratio	Slagging Tendency	Fouling Index (Fu)	Fouling Tendency
0	0.26	Low	0.88	Medium
5	0.34	Low	1.13	Medium
10	0.43	Low	1.5	Medium
20	0.63	Medium	2.4	Medium
30	0.84	Medium	3.65	Medium
40	1.07	High	5.25	Medium
50	1.31	High	7.23	Medium
60	1.58	High	9.63	Medium
70	1.89	High	12.52	Medium
80	2.23	High	15.16	Medium

The results indicate that increasing biomass fraction gradually increases both slagging and fouling tendencies. The calculated Base-to-Acid ratio (B/A) increased from 0.26 at 0% co-firing to 2.23 at 80% co-firing, indicating a transition from low to high slagging tendency as biomass utilization increases. Similarly, the fouling index increased from 0.88 to 15.16 due to the increasing alkali-related compounds, particularly CaO and K_2O contained in biomass ash. The increase in alkali compounds may promote ash deposition and sticky particle formation on heat transfer surfaces during long-term operation.

However, although the slagging and fouling tendency increased with higher biomass fraction, the ash fusion temperature of the biomass-coal blend remained higher than the normal CFB furnace operating temperature. The simulation results also showed that the furnace temperature gradually decreased from approximately 960.6 °C at 0% co-firing to around 855.5 °C at 80% co-firing due to the higher moisture content and lower heating value of biomass fuel. Since the operating temperature remained below the ash fusion temperature range, severe ash melting and bed agglomeration were not expected under the investigated operating conditions.

In addition to thermodynamic and environmental performance, a preliminary economic assessment was conducted to evaluate the feasibility of biomass co-firing implementation under different biomass fractions, as presented in Fig. 8 and Fig. 9. The results show that increasing biomass fraction from 5% to 80% gradually improves the economic performance under the investigated assumptions. The NPV increases from approximately -1.34 MUSD at 5% co-firing to around 16.30 MUSD at 80% co-firing, while the IRR increases from 9.29% to 14.84%. In addition, the payback period decreases from approximately 105 months to around 75 months. Operational economic analysis also indicates that fuel cost decreases from approximately 24.33 MUSD/y to around 21.96 MUSD/y, while annual cash flow increases from approximately 5.20 MUSD/y to around 7.21 MUSD/y as the biomass fraction increases.

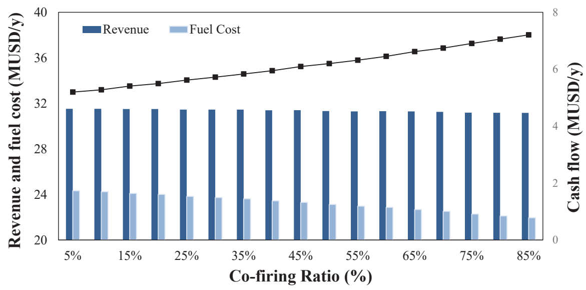

Fig. 8. Effect of biomass co-firing ratio on operational economic parameters.

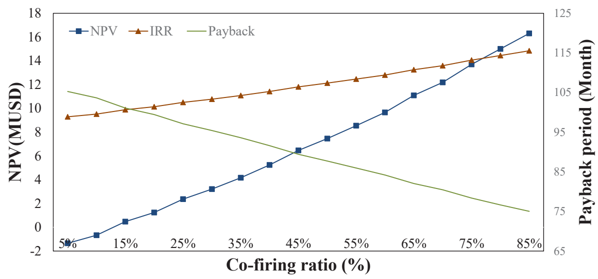

Fig. 9. Effect of biomass co-firing ratio on economic feasibility indicators.

Besides the economic benefit, higher biomass utilization also contributes to substantial reductions in specific CO_2 emissions. This indicates that biomass co-firing can provide simultaneous environmental and economic advantages while utilizing existing power plant infrastructure.

Compared to carbon capture technologies, biomass co-firing offers a relatively simpler decarbonization approach because it can be implemented with limited modification to the existing boiler system, particularly at low-to-medium biomass fractions. In contrast, carbon capture systems generally require higher capital investment, larger auxiliary power demand, and more complex operational integration.

4 Conclusions

This study evaluated the performance of high-ratio biomass co-firing up to 80% using woodchip in a 100 MW CFB power plant under full-load operating conditions. The results show that increasing biomass fraction leads to higher fuel consumption, increased auxiliary power demand, and gradual reductions in boiler and plant efficiency due to the lower heating value and higher moisture content of biomass fuel. The analysis of boiler heat losses indicates that latent heat losses associated with biomass moisture become more significant at higher biomass fractions.

From an environmental perspective, biomass co-firing significantly reduces specific CO_2 emissions, along with a decrease in SO_2 emissions due to the lower sulfur content of biomass. In addition, preliminary slagging and fouling assessment indicates increasing ash deposition tendency at higher biomass fractions because of the higher alkali content in biomass ash. Nevertheless, the ash fusion temperature remains higher than the normal CFB operating temperature, indicating relatively low risk of severe bed agglomeration under the investigated conditions.

The preliminary economic evaluation suggests that biomass co-firing remains economically feasible under the investigated operating conditions. Overall, the use of woodchip as a co-firing fuel shows promising potential for reducing carbon emissions in existing CFB power plants. However, higher biomass fractions may lead to reductions in thermal performance and increased operational challenges due to the lower heating value and higher moisture content of biomass fuel. The findings of this study provide practical insight into the performance characteristics of high-ratio biomass co-firing and may support future biomass utilization strategies in coal-fired power plants.

Reference

1. International Energy Agency (IEA), World Energy Outlook 2020 (IEA, Paris, 2020)
2. L. Liu, M.Z. Memon, Y. Xie, S. Gao, Y. Guo, J. Dong, Y. Gao, A. Li, G. Ji, Recent advances of research in coal and biomass co-firing for electricity and heat generation. Circ. Econ. 2, 100063 (2023). https://doi.org/10.1016/j.cec.2023.100063
3. T. Chen, Y. Zhao, S. Huang, Y. Jin, M. Wang, H. Feng, J. Yin, Influence of papermaking biomass co-firing on operation energy efficiency and gas emission stability of a coal-fired thermal power plant: A case study. Energy 327, 136484 (2025). https://doi.org/10.1016/j.energy.2025.136484
4. T. Varpiang, S. Suksri, P. Kuchonthara, Operational challenges in biomass co-firing systems. Energy Rep. 9, 6–9 (2023). https://doi.org/10.1016/j.egyr.2023.01.005
5. P.R. Wander, F.M. Bianchi, N.R. Caetano, M.A. Klunk, M.L.S. Indrusiak, Cofiring low-rank coal and biomass in a bubbling fluidized bed with varying excess air ratio and fluidization velocity. Energy 203, 117882 (2020). https://doi.org/10.1016/j.energy.2020.117882
6. T.-Y. Mun, T.Z. Tumsa, U. Lee, W. Yang, Performance evaluation of co-firing various kinds of biomass with low-rank coals in a 500 MWe coal-fired power plant. Energy 115, 954–962 (2016). https://doi.org/10.1016/j.energy.2016.09.060
7. IEA Bioenergy, Biomass Co-firing Technology Report (IEA Bioenergy, 2020)
8. PT PLN (Persero), Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) PLN 2025–2034 (PT PLN (Persero), Jakarta, 2025)
9. J. Lachman, M. Balaš, M. Lisý, H. Lisa, P. Milčák, P. Elbl, An overview of slagging and fouling indicators and their applicability to biomass fuels. Fuel Process. Technol. 217, 106804 (2021). https://doi.org/10.1016/j.fuproc.2021.106804
10. P. Basu, Circulating Fluidized Bed Boilers: Design, Operation and Maintenance (Springer International Publishing, Switzerland, 2015)
11. China National Technical Import and Export Corporation (CNTIC), Performance Test Report for Unit No. 1 of Coal Fired Steam Power Plant Project, Sumatera Barat, Indonesia, Document No. CNTIC-PADANG-TR-1401 (CNTIC, 2014)
12. A.D. Youlensha et al., Analisis Karakteristik Pengujian Cofiring Woodchip PLTU Teluk Sirih Unit 2, Laporan Kajian No. 14-011/KPK/KIT/2024 (PT PLN Indonesia Power, Jakarta, 2024)