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The Impacts of Woodchip Co-Firing on Boiler Efficiency and the Environment at the 100 MW CFB Sebalang Power Plant as a Green Energy Enhancement

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Abstract

Biomass co-firing in coal-fired power plants is one of the energy transition strategies that enables the utilization of existing power generation assets. This study evaluates the effects of woodchip co-firing on the circulating fluidized bed (CFB) boiler at PLTU Sebalang Unit 1 (2 × 100 MW) using woodchip co-firing ratios of 0%, 10%, 20%, and 30%. The parameters analyzed included gross load, gross and net energy production, fuel consumption across the four coal feeders, total fuel consumption, specific fuel consumption (SFC), gross calorific value (GCV), gross plant heat rate (GPHR), and net plant heat rate (NPHR). The results showed that increasing the woodchip co-firing ratio to 30% did not significantly reduce the gross load, which decreased only from 87.11 MW to 86.94 MW (approximately 0.20%). However, total fuel consumption increased from 267.06 tons to 328.50 tons, while SFC rose from 0.678 kg/kWh to 0.840 kg/kWh. The GPHR increased from 3,044.08 kcal/kWh to 3,448.24 kcal/kWh at a 30% woodchip co-firing ratio, whereas the NPHR increased from 3,369.01 kcal/kWh to 3,830.29 kcal/kWh. These findings suggest that woodchip co-firing can maintain load stability but results in higher fuel consumption and heat rate penalties because of the lower calorific value of woodchips, their potentially higher moisture content, and challenges associated with fuel homogenization and feeding. Therefore, implementing medium- to high-ratio woodchip co-firing requires stringent woodchip quality control, feeder calibration, combustion air optimization, and continuous heat rate monitoring based on actual operating data.

INTRODUCTION

Biomass co-firing in coal-fired power plants is a relatively rapid energy transition strategy because it utilizes existing boiler, turbine, generator, and electrical system infrastructure. This approach is particularly relevant for electricity systems that continue to rely on coal-fired power plants while seeking to reduce greenhouse gas emission intensity and diversify fuel sources. The literature suggests that co-firing can serve as a technical bridge between conventional coal-based power generation and increased renewable energy integration, particularly when supported by stringent fuel quality control and optimized boiler operation (Sami et al., 2001; Tillman, 2000; Baxter, 2005; Saidur et al., 2011).

Woodchips are among the most promising solid biomass fuels because they are derived from wood and forestry residues, exhibit relatively high reactivity, and can be blended with coal in specific combustion systems. However, woody biomass generally has a lower calorific value, higher moisture content, lower bulk density, and a more heterogeneous particle size distribution than coal. These characteristics increase the fuel mass required to produce the same energy output (Demirbas, 2004, 2005; McKendry, 2002; Nussbaumer, 2003).

Circulating fluidized bed (CFB) boilers offer high fuel flexibility because the fluidization process promotes intensive solid mixing, extended particle residence times, and relatively uniform furnace temperature distribution. Nevertheless, increasing the proportion of woodchips may still influence fuel feeding, fluidization behavior, char combustion, fly ash carryover, heat rate, and the stability of heat distribution within the furnace (Khan et al., 2009; Werther et al., 2000; Spliethoff & Hein, 1998; Teixeira et al., 2012). Therefore, evaluations based on actual operating data are essential to determine whether higher co-firing ratios remain operationally feasible while maintaining acceptable performance.

Fuel quality is a primary factor influencing co-firing performance. Parameters such as gross calorific value (GCV), moisture content, volatile matter, fixed carbon, bulk density, and particle size affect the heat release rate, combustion air requirements, flame stability, and burnout efficiency. Woody biomass typically has a higher volatile matter content but lower calorific value and energy density than coal. Consequently, the fuel feed rate often must be increased to maintain the desired power generation load (Jenkins et al., 1998; Obernberger & Thek, 2004; Obernberger et al., 2006; Qin & Thunman, 2015).

Specific fuel consumption (SFC) and heat rate are key indicators for evaluating the thermal and operational performance of co-firing. SFC represents the mass of fuel required to generate one unit of electrical energy, whereas heat rate represents the amount of thermal energy required to produce one unit of electricity. Increases in SFC or heat rate may result from lower effective calorific values, elevated moisture content, increased heat losses, feeder imbalances, or changes in combustion air requirements (Channiwala & Parikh, 2002; McKendry, 2002; Nussbaumer, 2003; Tillman, 2000).

In addition to energy performance, co-firing must also consider ash-related issues, including deposit formation, slagging, fouling, and corrosion. Biomass ash often contains high concentrations of alkali and alkaline earth elements, increasing its potential to form low-melting-point compounds. The transformation of K, Na, Cl, S, Ca, and Si during combustion influences superheater deposits, bed material agglomeration, and heat transfer performance (Vassilev et al., 2010, 2013a, 2013b; Bostrom et al., 2012; Bashir et al., 2012).

Ash deposits on heat transfer surfaces increase thermal resistance, reduce boiler efficiency, and elevate the risk of high-temperature corrosion. Therefore, evaluating the feasibility of co-firing based solely on load performance is insufficient. Comprehensive assessments should integrate heat rate, emissions, unburned carbon, ash chemistry, ash fusion temperature, and findings from actual deposit inspections (Bryers, 1996; Frandsen, 2005; Hansen et al., 2000; Zbogar et al., 2005).

Chlorine, sulfur, and alkali metals play critical roles in both corrosion and biomass deposit formation. Potassium chloride (KCl) and other alkali salts may deposit on superheater surfaces, whereas sulfur can promote sulfate formation that, under certain conditions, reduces the corrosive effects of chlorine. Consequently, the sulfur-to-chlorine (S/Cl) ratio, alkali content, and flue gas temperature should be evaluated collectively (Dayton et al., 1999; Glarborg & Marshall, 2005; Knudsen et al., 2004; Johansen et al., 2013).

Slagging and fouling indices are commonly used as preliminary screening tools; however, they should be interpreted with caution because biomass ash behavior does not always follow the same correlations established for coal ash. Recent studies emphasize combining operating data, fuel characterization, ash analysis, and thermochemical modeling to generate more reliable recommendations for coal–biomass co-combustion systems (Niu et al., 2016; Pronobis, 2005; Rizvi et al., 2015; Lachman et al., 2021; Xing et al., 2016).

From an industrial implementation perspective, co-firing evaluations should simultaneously consider technical and economic factors. Stable boiler performance does not necessarily indicate optimal primary energy utilization. Therefore, gross plant heat rate (GPHR) and net plant heat rate (NPHR) should be analyzed together with SFC, fuel calorific value, and fuel handling system capability to support operational decisions that balance efficiency, fuel supply costs, and long-term reliability (Hariana et al., 2023; Hedayati et al., 2022; Xing et al., 2016; Vamvuka & Zografos, 2004).

The novelty of this research lies in its systematic analysis of actual operating data obtained from a 100 MW CFB boiler at PLTU Sebalang under four woodchip co-firing scenarios (0%, 10%, 20%, and 30%). Unlike many previous studies that primarily rely on theoretical modeling or laboratory-scale experiments, this study uses real power plant operating data to evaluate the effects of woodchip co-firing on key performance indicators, including SFC, GPHR, NPHR, and feeder distribution balance. This approach provides practical insights that are directly applicable to commercial power plant operations and contributes to the growing body of knowledge on large-scale biomass co-firing implementation.

The contributions of this research are threefold: technical, economic, and environmental. From a technical perspective, it identifies co-firing ratios capable of maintaining stable boiler performance while maximizing biomass utilization. Economically, it provides operational data for evaluating the trade-offs between increased fuel consumption and potential efficiency losses against the benefits of renewable energy utilization and potential carbon credit opportunities. Environmentally, it supports the transition toward lower-carbon electricity generation by demonstrating the operational feasibility of biomass co-firing while identifying areas requiring further optimization. Ultimately, this research contributes to the broader objective of sustainable energy development in Indonesia.

METHODS

This study employed a descriptive quantitative approach to analyze woodchip co-firing test data obtained from PLTU Sebalang Unit 1 (2 × 100 MW). Four co-firing scenarios were evaluated: 0%, 10%, 20%, and 30% woodchips. The 0% scenario served as the baseline for conventional coal-fired operation. Each test was conducted over the same duration, allowing direct comparisons among scenarios.

The main parameters analyzed included average gross load, gross electrical energy, net electrical energy, fuel consumption in coal feeders A–D, total fuel consumption, specific fuel consumption (SFC), coal gross calorific value (GCV), woodchip gross calorific value (GCV), gross plant heat rate (GPHR), and net plant heat rate (NPHR). The analysis examined changes relative to the baseline, the net-to-gross energy ratio, indicated efficiency based on heat rate, and the coefficient of variation (CV) of feeder distribution to assess the uniformity of fuel flow.

Indicated efficiency was estimated from the relationship between the electrical energy equivalent of 860 kcal/kWh and the heat rate. This metric was used as a comparative performance indicator rather than as the actual thermal efficiency of the generating unit.

Table 1. Co-firing operation data of co-firing woodchip PLTU Sebalang 2 x 100 MW Unit 1

Yes	Parameters	Units	0%	10%	20%	30%
1	Average gross load	MW	87,11	87,09	87,06	86,94
2	Gross electrical energy	MWh	394,00	392,00	390,00	391,00
3	Net electrical energy	MWh	356,00	354,00	352,00	352,00
4	Test duration	Hours	4,50	4,50	4,50	4,50
5	CF A fuel consumption	ton	66,79	74,27	81,74	75,77
6	CF B fuel consumption	ton	66,55	74,02	81,48	87,68
7	CF C fuel consumption	ton	66,94	74,41	81,88	84,28
8	CF D fuel consumption	ton	66,78	74,24	81,69	80,77
9	Total fuel consumption	ton	267,06	296,93	326,79	328,50
10	Specific fuel consumption	kg/kWh	0,678	0,757	0,838	0,840
11	GCV coal	kCal/kg	4491,00	4491,00	4491,00	4491,00
12	GCV wood chips	kCal/kg	0	3202,00	3202,00	3202,00
13	GPHR	kCal/kWh*	3044,08	3295,59	3547,10	3448,24
14	NPHR	kCal/kWh*	3369,01	3649,52	3930,02	3830,29

*Note: GPHR and NPHR units are presented as kCal/kWh for heat rate consistency, even though the source table lists kCal/kW.

Table 2. Derivative indicators against baseline 0% woodchip

Indicator	0%	10%	20%	30%
Change in gross load (%)	0,00	-0,02	-0,06	-0,20
Gross energy change (%)	0,00	-0,51	-1,02	-0,76
Net energy change (%)	0,00	-0,56	-1,12	-1,12
Total change in fuel (%)	0,00	11,18	22,37	23,01
Change in SFC gross (%)	0,00	11,65	23,60	23,89
GPHR changes (%)	0,00	8,26	16,52	13,28
NPHR Changes (%)	0,00	8,33	16,65	13,69
Net-to-gross ratio (%)	90,36	90,31	90,26	90,03
Indicated gross efficiency (%)	28,25	26,10	24,25	24,94
Indicated net efficiency (%)	25,53	23,56	21,88	22,45
CV feeder distribution (%)	0,21	0,19	0,18	5,37

RESULTS AND DISCUSSION

Load Stability and Energy Production

The gross load at baseline 0% woodchips was 87.11 MW. In the co-firing ratio of 10%, 20%, and 30%, the gross load was 87.09 MW, 87.06 MW, and 86.94 MW, respectively. The decrease relative to baseline was only 0.02%, 0.06%, and 0.20%. These results show that CFB boilers are able to maintain almost constant power output even though the woodchip ratio is increased by 30%.

Gross electrical energy decreased from 394 MWh to 392 MWh, 390 MWh, and 391 MWh at a ratio of 10%, 20%, and 30%. The maximum relative decline occurred at a ratio of 20%, which is around 1.02%. Net electrical energy decreased from 356 MWh to 354 MWh at 10%, and 352 MWh at 20% and 30%. The net-to-gross ratio decreased from 90.36% at baseline to 90.03% at 30% woodchip. This decrease is small, but indicates a tendency to increase internal consumption or system losses when the woodchip fraction increases.

Fuel Consumption and Feeder Balance

Total fuel consumption increased from 267.06 tons at baseline to 296.93 tons at 10%, 326.79 tons at 20%, and 328.50 tons at 30%. The relative increase was 11.18%, 22.37%, and 23.01%, respectively. This increase is quite significant, while the load and energy production have changed only slightly. This means that in order to maintain almost the same electrical output, the system requires a larger mass of fuel when woodchips are added.

At 0%, 10%, and 20%, the feeder distribution is relatively balanced, with CV being around 0.21%, 0.19%, and 0.18%, respectively. However, at 30%, CV increased to 5.37%

because feeder B consumption reached 87.68 tons, much higher than feeder A of 75.77 tons. This imbalance needs to be a concern because it can signal material segregation, differences in mixture density, particle size variations, or feeder calibration issues. In CFB boilers, feed rate imbalances can affect heat distribution, local excess water, and fluidization stability.

Specific Fuel Consumption

SFC increased from 0.678 kg/kWh at baseline to 0.757 kg/kWh at 10%, 0.838 kg/kWh at 20%, and 0.840 kg/kWh at 30%. Compared to the baseline, the increase in SFC was 11.65%, 23.60%, and 23.89%, respectively. This is the main indicator of the specific fuel consumption penalty due to woodchip co-firing.

The increase in SFC can be explained by the difference in the calorific value and physical characteristics of the woodchip. The data shows that the GCV of coal is 4,491 kCal/kg, while the GCV of woodchip is 3,202 kCal/kg. This difference means that each kilogram of woodchip carries less energy than coal. If the moisture content of the woodchip is high, some of the combustion energy is also absorbed for water evaporation so that the effective energy that goes into the steam cycle becomes lower. Therefore, an increase in the mass rate of the fuel is a natural thermal consequence, but it still needs to be controlled through the drying and homogenization of the fuel.

Interestingly, the increase in SFC from 20% to 30% is relatively small, from 0.838 to 0.840 kg/kWh. This may indicate that the boiler control system is starting to reach consumption plateau conditions at that range, or that a momentary variation in operation is affecting the totalizer reading. Since the feeder distribution at 30% is more unbalanced, the interpretation of the SFC plateau needs to be verified with additional data such as actual moisture, O2 flue gas, CO, bed temperature, FEGT, and unburned carbon.

Heat Rate and Indicated Efficiency Analysis

GPHR increased from 3,044.08 kCal/kWh at baseline to 3,295.59 kCal/kWh at 10%, 3,547.10 kCal/kWh at 20%, and 3,448.24 kCal/kWh at 30%. The relative increase was 8.26%, 16.52%, and 13.28%. NPHR also increased from 3,369.01 kCal/kWh to 3,649.52 kCal/kWh, 3,930.02 kCal/kWh, and 3,830.29 kCal/kWh. The increase in NPHR relative to baseline was 8.33%, 16.65%, and 13.69%.

The gross efficiency was indicated to decrease from 28.25% at baseline to 26.10% at 10%, 24.25% at 20%, and 24.94% at 30%. Net efficiency is indicated to have decreased from 25.53% to 23.56%, 21.88%, and 22.45%. The 30% value is slightly better than 20% in terms of heat rate, although the SFC is about the same. This can be caused by combustion variations, feeder distribution, actual heat values of the mixture, or operating conditions during testing. Thus, the ratios of 20% and 30% should be compared to using longer time-series data.

Technical Implications for Coal Plant Operations

Operationally, data shows that woodchip co-firing can maintain the stability of the load of the Sebalang Unit 1 coal-fired power plant. However, the increase in total fuel consumption, SFC, GPHR, and NPHR shows an efficiency consequence. The first implication is the increasing need for the biomass supply chain. At a ratio of 30%, the total fuel mass increased by around 23.01% compared to the baseline, so the unloading, stockpile, conveyor, crusher, and feeder capacities need to be evaluated.

The second implication is the need for quality control of woodchips. Woodchips must have a controlled moisture content, uniform particle size, relatively stable bulk density, and free of contaminants that can increase deposits or corrosion. Pre-drying can increase the effective heat value and lower the heat rate penalty. Re-enumeration and filtering can reduce particle size variations and help with feeding stability.

The third implication is the need for combustion control. The increase in woodchips can change the needs of primary water, secondary air, excess water, and furnace temperature profiles. If the air settings are not optimal, combustion can produce higher CO, unburned carbon increases, or heat transfer decreases. Therefore, air-fuel ratio optimization and emission monitoring need to be carried out in conjunction with SFC and heat rate monitoring.

The fourth implication is the need for the integration of ash analysis. Although this article focuses on operations data, the literature suggests that biomass may increase the risk of slagging, fouling, agglomeration, and corrosion through the interaction of alkalis, chlorine, sulfur, and silica. Therefore, the implementation of co-firing above 20% needs to be accompanied by fly ash, bottom ash, ash fusion temperature, probe deposits, as well as periodic inspections of superheaters, reheaters, economizers, and water preheaters.

Recommendations for Operations and Advanced Research

For short-term operations, the 10% ratio appears to be the most moderate as the increase in SFC and heat rate is still lower than 20% and 30%, while the load remains stable. The 20% and 30% ratios have the potential to be implemented, but require stricter fuel quality control and economic evaluation of fuel mass increases and logistics needs.

At a ratio of 30%, the main concern is the feeder imbalance. Feeder calibration, flowability testing, particle size control, and mixture homogenization need to be performed before continuous operation. In addition, it is necessary to create an operation dashboard that links the ratio of co-firing, moisture, mixed GCV, feeder flow, O2, CO, bed temperature, steam flow, GPHR, NPHR, and emissions to obtain real-time operation recommendations.

Follow-up research needs to use higher-resolution time-series data, test repeats, and statistical analysis to distinguish the effects of co-firing ratios from variations in daily operations. A complete mass and energy balance is also needed to evaluate the boiler's efficiency more accurately. The integration of economic data, such as biomass prices, transportation costs, pre-treatment costs, and emission reduction values, will strengthen the feasibility analysis of implementation.

CONCLUSION

Based on the results of the woodchip co-firing tests conducted at PLTU Sebalang Unit 1 (2 × 100 MW), it can be concluded that the circulating fluidized bed (CFB) boiler demonstrated good operational flexibility in maintaining load stability across all evaluated co-firing ratios (0%, 10%, 20%, and 30%). Gross load remained within the range of 86.94–87.11 MW, with a maximum reduction of only 0.20% at the 30% woodchip co-firing ratio. Gross and net electrical energy production declined only marginally, with the largest reduction in gross electrical energy reaching approximately 1.02% at the 20% co-firing ratio. However, total fuel consumption increased substantially from 267.06 tons under the baseline condition to 328.50 tons at the 30% woodchip co-firing ratio, representing an increase of 23.01%. This increase in fuel consumption was primarily attributed to the lower gross calorific value (GCV) of woodchips (3,202 kcal/kg) compared with coal (4,491 kcal/kg) and the resulting thermal performance penalties.

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