

Technical Performance and Emission Impacts of High-Ratio Woodchip Biomass Co-Firing in a Subcritical Coal-Fired Power Plant

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Abstract. This study assesses the technical performance and emission characteristics of high-ratio biomass co-firing at PLTU Anggrek Gorontalo, a 2 × 25 MW subcritical coal-fired power plant in Indonesia. The investigation focuses on a 50% woodchip biomass substitution (on a thermal input basis) compared with a conventional 100% coal operation. Full-scale plant trials were conducted under steady-state conditions at 80–90% load to ensure operational consistency. Fuel properties were characterized through proximate and ultimate analyses, as well as higher heating value (HHV) determination. Key operational parameters—including boiler efficiency, steam pressure, temperature, mass flow rate, furnace temperature, and air preheater temperature—were continuously monitored. Stack emissions (CO₂, SO₂, NO_x, and O₂) were measured to evaluate environmental performance. The results indicate that 50% woodchip co-firing can be implemented without significant derating of plant capacity. Gross electrical output, main steam pressure, temperature, and flow rate remained comparable to baseline coal operation, while furnace and air preheater temperatures stayed within acceptable operating limits. However, gross specific fuel consumption increased from 1.13 to 1.22 kg/kWh despite the blended fuel exhibiting a higher gross calorific value. This suggests an efficiency penalty likely associated with suboptimal combustion dynamics and air–fuel mixing at high biomass fractions. In terms of emissions, a distinct trade-off was observed. NO_x concentrations decreased significantly under co-firing conditions, indicating improved nitrogen-related emission performance. Conversely, SO₂ concentrations increased relative to pure coal combustion, and CO₂ emissions rose slightly, accompanied by lower excess oxygen levels in the flue gas. Overall, the findings demonstrate that 50% woodchip co-firing is technically feasible in a subcritical coal-fired unit and offers substantial NO_x mitigation potential. Nevertheless, further combustion optimization, air distribution adjustment, and biomass quality control are necessary to minimize efficiency penalties and manage SO₂ emissions effectively.

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1. Introduction

Coal-fired power plants continue to represent one of the largest point sources of anthropogenic greenhouse gas (GHG) emissions globally, despite the rapid expansion of renewable energy technologies over the past decade. The IPCC Sixth Assessment Report (AR6) identifies the energy supply sector as contributing approximately one-third of total global GHG emissions in 2019, with emissions from energy systems increasing between 2015 and 2019, largely driven by the combustion of coal, oil, and natural gas. Although renewable deployment has accelerated, coal remains deeply embedded in many national power systems, particularly in emerging and developing economies where it provides baseload capacity, grid stability, and energy security. Consequently, the immediate and complete phase-out of coal-fired generation presents significant technical, economic, and social challenges.

Biomass co-firing has emerged as one of the most widely discussed near-term options for reducing the carbon intensity of coal power generation. Co-firing refers to the simultaneous combustion of coal and biomass in the same boiler, either by direct blending of solid fuels, by parallel firing in a separate biomass boiler with common steam cycle integration, or by indirect firing through biomass gasification and subsequent co-combustion of syngas with coal. When biomass is sourced sustainably, its biogenic CO₂ emissions are often treated as carbon neutral over the lifecycle, so partially substituting coal with biomass lowers net fossil CO₂ emissions per unit of electricity. In addition, many woody biomasses contain less sulfur and ash-forming minerals than typical power-station coals, which can lead to reductions in sulfur dioxide (SO₂) and, under some conditions, nitrogen oxides (NO_x) and particulate matter (PM).

Recent research from 2020–2025 provides growing empirical evidence on the technical and environmental performance of coal–biomass co-firing systems. Abid et al. (2020) modeled biomass gasification coupled with a 330 MW subcritical coal-fired boiler and reported that cofiring syngas derived from various solid wastes reduced NO and SO₂ volume fractions in the flue gas, while maintaining boiler efficiencies above 90% and overall system efficiencies above 82%. Zhang et al. (2020) similarly analyzed biomass gasification integrated with a coal-fired boiler under different loads and found that, with appropriate air-to-fuel ratios, co-firing can lower pollutant emissions while sustaining acceptable thermal performance. These studies highlight that, at the boiler and system scale, co-firing can simultaneously reduce specific emissions and preserve efficiency, provided that fuel preparation and operating parameters are carefully optimized.

At the scale of individual power plants, more detailed techno-economic assessments have been carried out. For the Indonesian context, Arifin et al. (2023) evaluated pilot co-firing projects in three pulverized coal (PC) units using 5% biomass on an energy basis. They reported that plant efficiency changes correlate roughly linearly with the heating value of biomass, while furnace exit gas temperature remains largely unaffected at low co-firing ratios. Environmentally, SO₂ emissions were reduced by up to 34%, and NO_x emissions also decreased depending on the nitrogen content of the biomass, although generating costs increased slightly because biomass fuel is more expensive per unit of energy than coal. These results suggest that modest co-firing ratios can deliver meaningful reductions in local air pollutants and GHG emissions with limited performance penalties.

Beyond individual plants, regional and national analyses illustrate that co-firing's aggregate impact depends strongly on deployment scale and feedstock supply. A 2025 assessment by the Centre for Research on Energy and Clean Air (CREA) estimated that Indonesia's biomass co-firing initiatives—primarily targeting 5–10% biomass substitution in state-owned coal units— could reduce SO₂, NO_x, and PM emissions by under 10% at the

plants where co-firing is applied and only 1.5–2.4% of aggregate coal-power emissions at national level under current plans. This gap between promising unit-level performance and modest system-level impact underscores that co-firing must be scaled substantially and combined with broader power-sector decarbonization to align with AR6 mitigation pathways.

Within the broad category of biomass fuels, woody feedstocks such as woodchips, sawdust, and wood pellets are among the most widely used in co-firing projects, due to their relatively homogeneous quality, established supply chains, and compatibility with existing handling systems. Bhoi and Sarkar (2025) performed a detailed modeling study on co-firing loblolly pine biomass with waste coal in 100 MW and 600 MW units under subcritical and supercritical conditions. They found that increasing the biomass fraction from 0% to 100% could improve net plant efficiency by 3–8% and, when combined with CCS, reduce CO₂ emissions by more than 80%, with SO₂ and PM emissions approaching zero. Although their case focused on pine biomass and waste coal, the findings indicate that woody biomass with a favorable calorific value and low sulfur content can deliver significant performance and emission benefits in appropriately designed or retrofitted plants.

At the same time, the global mitigation literature emphasizes that power-sector pathways compatible with limiting warming to well below 2 °C require rapid reductions in the emissions intensity of electricity, not only in absolute emissions. While full replacement of coal by renewables and storage represents the long-term solution, near-term measures like biomass cofiring can reduce the emissions intensity of existing plants, extend their service life under stricter emission regulations, and provide flexibility as variable renewable energy shares increase. However, the net climate benefit of co-firing depends on feedstock supply chains, land-use impacts, and life-cycle assessment, making plant-scale studies on performance and stack emissions a necessary but not sufficient condition for judging sustainability.

Despite the growing body of work summarized above, several knowledge gaps remain, particularly with regard to the co-firing of non-densified woodchip biomass in large PC boilers. Much of the literature focuses either on (i) small-scale experimental furnaces, (ii) gasification-based co-firing systems, or (iii) fully densified fuels such as wood pellets or torrefied biomass. Studies that explicitly investigate how varying woodchip co-firing ratios affect boiler operating parameters (e.g., furnace temperature, heat transfer, unburned carbon in ash) concurrently with key emission indicators (CO₂, SO₂, NO_x, and PM) under realistic operating conditions are still limited, especially for units in the 300–600 MW capacity range. In addition, there is a need to understand how co-firing woodchips influences trade-offs between different pollutants; for instance, lower SO₂ due to reduced fuel sulfur versus potential changes in NO_x formation associated with altered flame temperature and stoichiometry.

In this context, the present study focuses on the combined-fuel operation of a coal-fired power plant using woodchip biomass and its emission effects. The overarching objective is to provide a comprehensive technical and environmental analysis of woodchip co-firing that can inform both plant-level operation and broader policy discussions. Specifically, the study aims to: (1) characterize the fuel properties of coal and woodchip mixtures relevant to combustion behavior; (2) assess how different woodchip co-firing ratios affect boiler performance indicators such as efficiency, flue-gas temperature, and unburned carbon; and (3) quantify the resulting changes in stack emissions of CO₂, SO₂, NO_x, and particulate matter under representative operating conditions. By systematically linking fuel characteristics, combustion performance, and emission outcomes, this work seeks to clarify the conditions under which woodchip co-firing can deliver robust emission reductions

without compromising plant reliability, thereby contributing to the design of safe and environmentally sound co-firing strategies in coal-dominated power systems.

2. Methodology

This study adopts an experimental approach on an operating coal-fired power plant, PLTU Anggrek Gorontalo, which consists of two subcritical units with an installed capacity of 2×25 MW. The methodology is structured to (i) establish a reliable baseline for 100% coal firing, (ii) implement and operate a 50% woodchip biomass co-firing scenario on one unit, and (iii) compare performance and emission parameters between both operating modes. The following subsections describe the plant selection, fuel characterization, test matrix design, measurement systems, data acquisition, and data analysis procedures.

2.1 Plant selection and operating conditions

PLTU Anggrek Gorontalo is chosen as the reference case because it exemplifies a typical medium-scale Indonesian coal-fired power plant with stable baseload operation and accessible boiler and stack monitoring points. One unit (Unit 1) is designated for experimental co-firing tests, while the other unit (Unit 2) operates normally at 100% coal and serves as a reference when needed.

The tests are carried out at steady loads of 80–90% of rated capacity to reflect typical operating practice and to minimize load-induced variability. For each test condition, the unit is operated in a stable regime (constant load, constant excess air, stable main steam pressure and temperature) for a minimum of 2–3 hours before data recording. All existing plant control systems (boiler master, feedwater control, air–fuel ratio control) are kept in automatic mode, and only fuel feed rates and distribution are adjusted to achieve the target co-firing ratio.

2.2 Fuel preparation and characterization

Two main fuels are used: standard boiler coal and woodchip biomass. Representative samples of each fuel are collected before testing and subjected to laboratory characterization. Proximate and ultimate analyses are performed to determine moisture, volatile matter, fixed carbon, ash content, elemental composition (C, H, N, S, O), and higher heating value (HHV). Particle size distribution is measured using sieve analysis to verify that woodchips are compatible with the plant's fuel handling and feeding systems. For the 50% co-firing case, the target ratio is defined on an energy (thermal input) basis, i.e., 50% of the total boiler heat input is supplied by woodchips and 50% by coal. Based on the measured HHV of each fuel, the required mass flow rates of coal and woodchips are calculated and used to set the feeding equipment (belt conveyors, feeders, and/or dedicated biomass feeders). Before feeding, woodchips are inspected for excessive moisture, contaminants, and oversized pieces; if required, pre-drying and size reduction measures are applied to stay within predefined specifications.

2.3 Experimental test matrix

The experimental program consists of two main operating modes:

- a. Baseline mode (100% coal): The boiler is fired with its normal coal fuel at standard operating conditions. This mode is used to establish reference values for boiler efficiency, flue-gas composition, and stack emission factors
- b. Co-firing mode (50% woodchip–coal blend): The boiler is operated with a combined fuel mixture such that 50% of the thermal input is provided by woodchip biomass. Air distribution, mill loading, and burner settings are adjusted to maintain a stable flame and similar steam production to the baseline case.

Each mode is tested in at least three independent runs on different days to capture operational variability. For each run, after the unit reaches steady state, continuous monitoring of process and emission variables is carried out over a period of 60–120 minutes, and all relevant parameters are logged at 1-minute intervals. Shorter “transient” periods during fuel switching are not included in the analysis.

3. Results

3.1 Boiler operating performance

The technical performance table shows that the boiler operated in a very similar range under 50% woodchips co-firing compared with pure coal firing. The gross load only decreased slightly, from 25.37 MW for 100% coal to 24.85 MW for 50% woodchips. This small difference would appear in the load graph as two bars (or points) at almost the same height, indicating that the unit can essentially maintain its design output even when half of the heat input is supplied by woodchips.

Tabel 1. Operating performance with difference Fuel

No	Indicator (Average)	100% Coal	Woodchips 50%
1	Load (MW Gross)	25,37	24,85
2	Main Steam Pressure (MPa)	4,57	4,44
3	Main Steam Temperature (°C)	473,84	460,93
4	Mainsteam Flow (T/h)	122,24	121,86
5	Furnace Temperature (°C)	769,42	763,61
7	Air Heater Inlet Temperature & Outlet Temperature (°C)	205,32 & 181,56	205,88 & 182,87
8	Total Coal Flow (T/h)	28,67	30,22

Adopted from Logsheet PLTU Anggrek 2 x 25 MW (2022)

Main steam parameters confirm this conclusion. The steam pressure decreases marginally from 4.57 MPa (coal) to 4.44 MPa (woodchips), and the main steam temperature drops from 473.84 °C to 460.93 °C. These reductions are modest and stay within typical operating limits, suggesting that heat transfer in the boiler and superheater is still sufficient to produce high-quality steam. In the graphs of pressure and temperature versus fuel mode, the trend would show a slight decline but no drastic deviation, reinforcing the statement in the report that boiler parameters remain within normal operating limits during the co-firing test.

3.2 Furnace and air heater temperature behavior

Furnace temperature is a key indicator of combustion intensity and flame stability. The average furnace temperature for 100% coal is 769.42 °C, while for 50% woodchips it is 763.61 °C. This slight decrease of less than 6 °C is negligible in practical terms and suggests

that the flame remains stable and the heat release in the furnace is comparable under both operating modes. On a graph of furnace temperature versus fuel configuration, the two bars would be nearly the same height, which visually supports the conclusion that co-firing does not significantly cool the combustion zone.

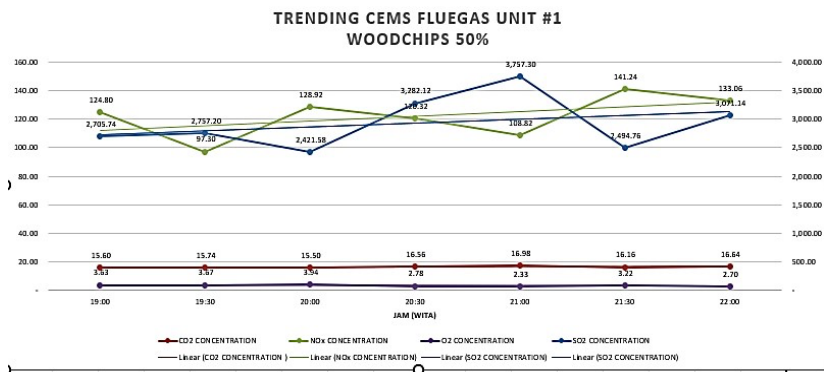


Figure 1: Trend Line Flue gas temperature with existing operation
Source: Cofiring Report PLTU Anggrek 2x25MW (2022)

Similarly, the air heater inlet and outlet temperatures are almost identical between the two cases. For 100% coal, the inlet and outlet temperatures are 205.32 °C and 181.56 °C; for 50% woodchips, they are 205.88 °C and 182.87 °C. The graphs corresponding to these values would show almost overlapping points. This indicates that the heat recovery from flue gas to combustion air is not negatively affected by switching to a 50% woodchips blend. In other words, the back-end heat exchange performance remains stable, which is important for both efficiency and equipment protection.

3.3 Fuel flow and specific fuel consumption

An important difference between the two operating modes lies in the total coal flow and specific fuel consumption (SFC). The total coal flow increases from 28.67 t/h under 100% coal firing to 30.22 t/h under 50% woodchips co-firing. This might initially appear counterintuitive because biomass is supposed to replace some of the coal. However, the reported SFC data clarify the situation:

- SFC increases from 1.13 kg/kWh for 100% coal to 1.22 kg/kWh for the 50% woodchips case.
- At the same time, the measured gross calorific value (GCV) of the fuel blend increases from 3185.21 kcal/kg (coal) to 3458.60 kcal/kg (woodchips 50%).

Table 2. Fuel consumption difference while cofiring mode

No	Indicator (Average)	100% Coal	Woodchips 50%
1	SFC (kg/KWh)	1,13	1,22
2	Gross Caloric Value (Kcal/Kg)	3185,21	3458,60

Adopted from Logsheet PLTU Anggrek 2 x 25 MW (2022)

If these data are plotted, the SFC graph would show a clear upward shift for the co-firing case, while the GCV graph would show a higher bar for the woodchips blend. The combination of higher GCV but also higher SFC suggests that, although the blended fuel has more energy per kilogram in laboratory tests, the boiler-turbine system does not convert that additional fuel quality into proportional additional useful work.

Several explanations are plausible. First, the combustion and air distribution settings may not yet be fully optimized for the 50% woodchips mixture, leading to slightly higher heat losses (for example, via unburned carbon, higher flue gas losses, or suboptimal excess air levels). Second, operators may deliberately increase the coal feed rate to maintain a stable flame when introducing a large share of biomass, which raises the total amount of fuel consumed per kWh even though part of the energy comes from woodchips. From an operational point of view, the SFC graph clearly signals an efficiency penalty associated with the current co-firing configuration. While the plant can maintain its load, it does so at the cost of burning more fuel per unit of electricity produced.

3.4 Emission behavior: SO₂, NO_x, CO₂, and O₂

The emission table shows contrasting trends for SO₂ and NO_x. For 100% coal operation, the average SO₂ concentration is 1973.97 mg/m³, whereas during 50% biomass co-firing it increases to 2892.52 mg/m³. NO_x, on the other hand, decreases from 180.56 mg/m³ to 121.69 mg/m³. CO₂ concentration rises slightly from 15.54% to 16.17%, and O₂ decreases from 3.90% to 3.18%.

In the corresponding bar charts, the SO₂ bar for the 50% woodchips case would stand noticeably higher than the coal-only bar, indicating a significant increase in measured SO₂ concentration. This result is somewhat unexpected because wood-based biomass generally contains less sulfur than coal. The likely reasons are operational and fuel-related: the higher overall fuel consumption (as indicated by SFC) increases the total sulfur input; batch-to-batch variability in coal sulfur content may also play a role; and changes in combustion conditions might influence how sulfur is oxidized and measured in the stack. The report also notes that SO₂ during 50% woodchips co-firing is higher than during 40% sawdust co-firing, reinforcing that both the type of biomass and the operating strategy strongly affect sulfur emissions. The NO_x graph tells a more positive story. The bar for NO_x under 50% biomass co-firing is clearly lower than that for the 100% coal case (and lower than the 40% sawdust test, according to the narrative). This aligns with established knowledge that biomass typically has lower fuel nitrogen and that altered flame temperature profiles and air distribution in co-firing modes can suppress NO_x formation. The decrease in excess oxygen (reflected in lower O₂ concentration in flue gas) also contributes to lower thermal and fuel NO_x formation.

Table 2. Emission Perform by dual fuel

No	Indicator (Average)	100% Coal	Biomassa 50%
1	SO ₂	1973,97 mg/m ³	2892,52 mg/m ³
2	NO _x	180,56 mg/m ³	121,69 mg/m ³
3	CO ₂	15,54 %	16,17 %
4	O ₂	3,90 %	3,18 %

Adopted from Logsheet PLTU Anggrek 2 x 25 MW (2022)

The CO₂ and O₂ graphs provide additional insight into combustion conditions. A higher CO₂ concentration together with lower O₂ suggests that the furnace is being operated with slightly lower excess air during co-firing. This can improve thermal efficiency to a point, but, combined with higher SFC, it also confirms that more total fuel is being burned to obtain nearly the same power output. For climate evaluation, one must remember that part of the CO₂ now comes from biogenic carbon in woodchips, which is treated differently from fossil CO₂ in life-cycle assessments. However, the stack concentration alone does not show this distinction; it mainly reflects combustion stoichiometry and total fuel flow.

4. Discussion

This discussion interprets the co-firing test results at PLTU Anggrek (100% coal vs. 50% woodchips) by referring to the attached technical and emission tables and their corresponding graphs. The goal is to understand not only whether the plant can operate with 50% biomass, but also what happens to efficiency and emissions under this condition.

4.1 Overall technical behaviour of the boiler

The technical table shows that all key boiler parameters during 50% woodchips co-firing remain close to those in the 100% coal baseline. Gross load decreases only slightly, from 25.37 MW to 24.85 MW. Main steam pressure declines from 4.57 MPa to 4.44 MPa, and steam temperature from 473.84 °C to 460.93 °C. Mainsteam flow also changes very little, from 122.24 t/h to 121.86 t/h.

If we look at the corresponding graphs (for example, bar charts of load, pressure, temperature, and flow for the two fuel modes), the bars for 100% coal and 50% woodchips would appear almost the same height. This visual impression confirms the verbal conclusion in the report: boiler operation “remains within normal limits” during the co-firing test. There is no evidence of severe derating, unstable steam conditions, or major control problems. From an operational standpoint, this is a very important result. It means that, at least for the test period, the plant can substitute 50% of its thermal input with woodchips without sacrificing its ability to produce (almost) full load or maintain acceptable steam conditions to the turbine. In many retrofit projects, the fear is that high biomass fractions will destabilize combustion or force a significant reduction in load; the data and graphs here suggest that this is not the case for woodchips at PLTU Anggrek.

4.2 Furnace and air-heater temperature profiles furnace

Temperature is a direct indicator of combustion intensity. In the table, furnace temperature drops only slightly from 769.42 °C (100% coal) to 763.61 °C (50% woodchips). In a line or bar chart showing furnace temperature for the two cases, the difference would be barely noticeable. This implies that heat release in the furnace is essentially preserved under co-firing. The air heater inlet and outlet temperatures tell a similar story. For coal operation, the inlet/outlet temperatures are 205.32 °C and 181.56 °C; under 50% woodchips, these become 205.88 °C and 182.87 °C. The graphs of these values would show almost overlapping bars, indicating that the back-end heat exchange between flue gas and combustion air is unaffected in any meaningful way. Together, the furnace and air-heater temperature graphs support three key interpretations:

1. Combustion remains stable. There is no sign of major cooling of the flame or significant reduction in flue-gas temperature at the boiler exit.

2. Heat transfer surfaces stay effective. The air heater appears to operate in the same temperature regime, suggesting no substantial fouling or degradation during the short test.
3. Control setpoints are preserved. The small differences likely result from normal operational variability rather than systematic impact of co-firing.
In other words, from a thermal-process perspective, the boiler “feels” very similar whether it is firing 100% coal or a 50% coal–woodchips blend.

4.3 Specific Fuel Consumption and fuel quality: an efficiency penalty

The more interesting – and more challenging – part of the interpretation lies in the fuel and efficiency indicators. The table shows that the gross Specific Fuel Consumption (SFC) increases from 1.13 kg/kWh for 100% coal to 1.22 kg/kWh for 50% woodchips. At the same time, the Gross Caloric Value (GCV) of the fuel blend *increases* from 3185.21 kcal/kg (coal) to 3458.60 kcal/kg (woodchips 50%). If we plot these indicators, two graphs emerge:

1. An SFC graph, where the bar for “Woodchips 50%” stands clearly higher than the bar for “100% Coal”.
2. A GCV graph, where the “Woodchips 50%” bar is higher than the “100% Coal”

This combination is counterintuitive. In theory, a higher-GCV fuel should allow lower SFC for the same load, *if* combustion and heat-recovery efficiencies remain constant. The fact that SFC goes up when GCV goes up indicates that the plant is not yet converting the higher laboratory-measured energy content into proportionally higher useful energy at the turbine shaft.

4.4 Emission trends: gains in NOx, challenges with SO₂

The emission table and the related graphs provide a nuanced picture of environmental performance. For 100% coal operation, the average emissions are:

- SO₂: 1973.97 mg/m³
- NOx: 180.56 mg/m³
- CO₂: 15.54%
- O₂: 3.90%

Under 50% biomass (woodchips) co-firing, the measured values change

- SO₂: 2892.52 mg/m³
- NOx: 121.69 mg/m³
- CO₂: 16.17%
- O₂: 3.18%

4.5 SO₂: an unexpected increase

In the SO₂ bar chart, the bar representing “Biomass 50%” stands significantly higher than the “100% Coal” bar. The narrative in the report also notes that SO₂ at 50% woodchips is higher than 100% coal case. This is somewhat counter to expectations, because wood-based biomass generally contains less sulfur than coal

5. Conclusion

1. The experimental results at PLTU Anggrek Gorontalo demonstrate that high-ratio co-firing with 50% woodchip biomass is technically feasible: the unit was able to operate close to its nominal 25 MW capacity, with main steam pressure,

- temperature, flow, and furnace/air-heater temperatures remaining within normal operating limits and without evidence of instability or severe derating.
2. Despite this technical success, the current co-firing configuration imposes a clear efficiency penalty. Gross specific fuel consumption increases from 1.13 kg/kWh (100% coal) to 1.22 kg/kWh (50% woodchips), even though the blended fuel has a higher gross calorific value. This indicates that combustion, air–fuel distribution, and/or heat-transfer processes are not yet fully optimized for the woodchip–coal blend, and that additional tuning is required to translate fuel quality into useful output.
 3. The emission analysis reveals important trade-offs: 50% woodchip co-firing significantly reduces NO_x concentrations at the stack, consistent with lower fuel nitrogen and altered flame characteristics, but measured SO₂ concentrations increase compared with the 100% coal baseline. At the same time, CO₂ concentration rises slightly and O₂ decreases, indicating operation with lower excess air and higher overall fuel throughput. These findings highlight that co-firing improves some environmental indicators while potentially worsening others if fuel quality and sulfur input are not carefully controlled.
 4. Overall, the study shows that woodchip co-firing at high ratios can be a practical transitional strategy for reducing the carbon intensity and NO_x emissions of existing coal-fired power plants, provided that it is accompanied by systematic combustion tuning, robust monitoring, and stricter management of coal and biomass properties (especially sulfur content, moisture, and particle size). Without such measures, the benefits in NO_x and partial decarbonization may be partially offset by increased fuel consumption and elevated SO₂ emissions.
 5. The results are inherently plant-specific but offer valuable guidance for similar medium-scale subcritical units in Indonesia and other coal-dependent systems. Future work should include longer-term testing, a wider range of co-firing ratios, detailed ash and slagging/fouling assessments, continuous emission monitoring, and life-cycle carbon analysis to better quantify the net environmental benefits and to identify an optimal operating window where technical performance, efficiency, and emissions are simultaneously acceptable.

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