# Sawdust Co-firing Operation Test on Pulverized Coal Boiler Power Plant

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**Abstract.** In 2021, Indonesia's renewable energy usage reached 15%, short of the 23% target set for 2025. To increase the renewable energy mix, PLN implemented biomass co-firing in existing coal-fired power plants. Indonesia's industrial waste has a biomass potential of 15,635.7 MWe, which still needs processing and adaptation to the current boiler specifications to keep investment costs low. Tests were conducted on a 300 MW pulverizer-type boiler power plant, designed for coal with a heating value of 4,200 kCal/kg, using 5% sawdust biomass. The purpose was to assess the impact of sawdust addition on plant equipment and emissions by comparing coal-biomass mixture combustion to 100% coal combustion. Sawdust, having lower sulfur content, lower heating value, and higher volatile matter than coal, led to the mill working harder, as shown by increased mill current and outlet temperature. However, the air heater's performance and steam production remained unchanged. Specific Fuel Consumption decreased by 0.01 kg/kWh during co-firing. Environmental emissions also changed, with $SO_2$ emissions reducing by 14.54 mg/Nm$^3$ and NOx emissions by 4.95 mg/Nm$^3$ during co-firing compared to using coal alone.

**Keywords:** co-firing, sawdust, biomass, boiler, pulverizer.

## 1 Introduction

As a developing nation, Indonesia's demand for electrical energy is increasing alongside its economic growth and national development. Over the last decade, electricity demand surged by 81 TWh in 2021, even accounting for the drop in consumption during the Covid-19 pandemic in 2020. The Indonesian government has tasked PLN with providing electrical energy across the country. Over the past ten years, the power generation capacity has risen significantly, reaching 30 TW in 2021 [1]. Indonesia's


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electricity production is primarily from coal-fired thermal power plants, followed by gas-powered plants and renewable energy sources. According to the General National Energy Plan (RUEN), by 2025, the government aims for an energy mix comprising at least 23% renewable energy, 30% coal, 25% oil, and 22% natural gas [2].

To reach the 2025 energy mix target, PLN must increase renewable energy from 15% in 2021 to 23%. In Indonesia, hydroelectric plants lead renewable generation, followed by geothermal and biomass. Challenges include high costs, underdeveloped technology, and reliance on imported equipment.

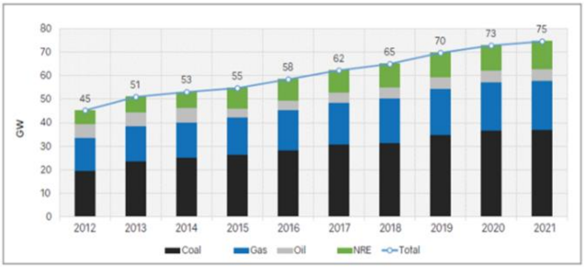


**Fig. 1.** Capacity of Installed Powerplants in Indonesia

To enhance the renewable energy mix, PLN has proposed several programs, including biomass co-firing in coal-fired power plants. This approach is seen as an efficient way to rapidly increase renewable energy usage without significant investment, as it leverages the existing infrastructure of coal-fired power plants (PLTU) and also helps address waste management issues. Several studies have discussed about co-firing on coal-fired power plant using certain types of biomass [3], [4].

Biomass, sourced from plants, animals, agricultural residues, and organic waste, is abundantly available in Indonesia. Industrial residues from palm oil, cassava, pulp and paper, sugarcane, rice, and wood contribute significantly to biomass resources, totaling 15,635.7 MWe distributed nationwide [5], [6]. Advantages of utilizing biomass as an energy source include the regrowth potential of the plants used, lowering emission levels and reducing waste, and easy availability across various regions [7]. However, one drawback of biomass utilization is the need for extensive land for consistent long-term supply, the long lifespan of plants, non-year-round harvesting, and adequate biomass management technology for immediate use [8].

The concept of co-firing involves burning two or more different types of materials simultaneously. co-firing technology is not new; several countries have been co-firing biomass in coal-fired thermal power plants. There are several methods of co-firing implementation, including direct co-firing, indirect co-firing, and parallel co-firing. In the direct co-firing method, biomass is directly introduced into the furnace along with coal. The drawback of direct co-firing are the potential for slagging and fouling[9], [10], limited co-firing ratios, and restricted types of biomass that can be used. The indirect co-firing method requires the addition of a gasifier to convert solid biomass into gas fuel. The advantage of indirect co-firing are the reduced potential for slagging formation, gasification processes reduce gas residence time, and various types of biomass can be used. The parallel co-firing method requires the installation of a separate biomass boiler to produce steam in coal-fired power plants. This method allows for an increase in the percentage of biomass in co-firing and reduces the contamination effects of biomass in coal-fired boiler combustion [11].

The scheme of the co-firing method used for burning a mixture of biomass with coal can be seen at Figure 2 [12].

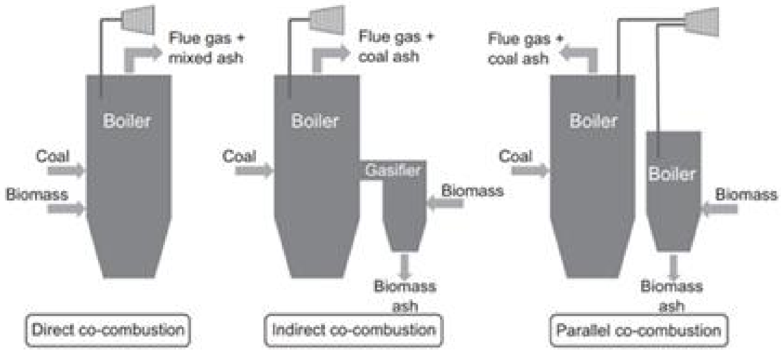


**Fig. 2.** Coal-Biomass Co-firing Method

The application of co-firing, observed in various countries as depicted in **Table 1** [13], involves opting for direct co-firing among the available methods for implementing it in existing coal-fired power plants in Indonesia. This choice is due to its omission of the need for additional facilities, resulting in minimal investment costs and swift implementation.

An essential step in utilizing biomass for co-firing is identifying the suitable type of biomass. Besides considering biomass availability around the power plant, it's crucial to align the chosen biomass's characteristics with the power plant boiler fuel specifications.

Biomass encompasses all materials originating from living organisms. Fundamentally, coal and biomass share a common origin, differing only in the time span: coal derives from plants fossilized over centuries, whereas biomass comes from recently harvested plants. The characteristics testing conducted for coal can also be applicable to testing biomass characteristics.

**Table 1.** Biomass Co-firing Implementations

| Powerplant Commissioning Time | Capacity Coal Fired Unit | Coupling Form | Biomass Fuel | Co-Combustion Ratio of Heat |
|---|---|---|---|---|
| Shilquan Power Plant / 2005 | 400t/h high temperature and high-pressure boiler | Direct Co-Firing | Wheat-straw, corn stalk | 18,6% (Design) |
| Baoji No 2 Power Generation Co., Ltd / 2010 | 5% - 8 % (Actual) | Direct Co-Firing | Straw, molding biomass | 6,76% - 21,90% |

| | | | | |
|---|---|---|---|---|
| Datang Changsan Thermal Power Plant / 2018 | 660 MW | Indirect Co-Firing | Straw, rice husk, waste wood | 3% |
| Huadian Xiangyang Power Plant / 2018 | 600 MW | Indirect Co-Firing | 50% rice husk, straw<br>50% biomass briquette | 1,8% |
| Changyuan Jingmen Power Plant / 2016 | 640 MW | Indirect Co-Firing | Rice husk, straw | 1,7% |
| Finnish Kymijarvi Power Plant / 1998 | 167 MW/240 MW | Indirect Co-Firing | Wood based biomass, waste recycling fuel | 15% - 30% |
| Finnish Vaskiluoto Power Plant / 2014 | 560 MW (240 MW/170 MW) | Indirect Co-Firing | Dry wood-based biomass | 25% |
| British Tibury Power Plant / 2014 | 712 MW | Direct Co-Firing | Forest tree, wood pellet | ~100% |
| British Fiddlers Ferry Power Plant / 1995 | 4 * 500 MW | Direct Co-Firing | Pressed waste wood pellet fuel, olive core and other biomass | 20% |

To understand the traits of biomass, one can conduct laboratory tests to analyze its composition as primary data, complemented by gathering information from multiple sources as secondary data. The parameters for assessing biomass characteristics are outlined in **Table 2** [14].

**Table 2.** Analytical Methods for Biomass Parameter Analysis

| Parameter | Analytical Methods | Parameter | Analytical Methods |
|---|---|---|---|
| Moisture Content | CEN/TS 14774-1 | Bromine Content | CEN/TS 15289 |
| Ash Content at 550°C | CEN/TS 14775 | Fluorine Content | CEN/TS 15289 |
| Ash Content at 815°C | ISO 1171 | Ash-Melting Behavior | ISO 540 |
| Volatile Matter | CEN/TS 15148 | Major Elements (Na, K, Ca, Mg, Si, P, Fe, Al, Ti) | CEN/TS 15290 (Part A) |
| Calorific Value | CEN/TS 14918 | Minor and Trace Elements (As, Be, Cd, Cr, Co, Cu, Mn, Ni, Pb, Se, TI, V, Zn) | CEN/TS 15297 |
| C, H, N Content | ASTM D5373 | | |
| Sulfur Content | ASTM D4239 | Mercury Content | CEN/TS 15297, ASTM D6722 |
| Chlorine Content | CEN/TS 15289, ASTM D6721 | Bulk Density | CEN/TS 15103 |

Non-wood biomass generally contains higher levels of ash, potassium, and phosphorus compared to wood. The increased alkali content, when combined with silica, can lead to greater slagging and fouling in boilers. On the other hand, wood biomass varies in ash content, influenced by factors like bark retention during harvesting, but typically, wood has lower ash content than non-wood biomass.

In contrast to coal, biomass tends to have higher volatile matter and lower carbon and ash content, resulting in more reactive combustion and longer flames. Biomass also has lower inherent moisture, making it easier to dry, but with lower calorific value. Biomass sulfur content is usually lower than coal, aiding in reduced SOx emissions. Using biomass in co-firing helps reduce $CO_2$, SOx, and NOx emissions.

Wood biomass has calorific values akin to low-rank coal but requires pre-treatment before use, like conversion into wood powder, chips, or pellets tailored to boiler needs, as detailed in **Table 3** [11]. However, wood powder biomass poses lower risks of spontaneous combustion compared to coal but needs careful handling during storage and feeding. One downside of biomass co-firing is its higher ash and chlorine content, which can impact boiler equipment quality.

**Table 3.** Boiler operation Specification on Co-firing Operation

| Co-Combustion System | Analytical Methods |
|---|---|
| Pulverized Combustion | Fuel type: coal, sawdust, and fine shavings<br>Particle type: < 10 – 20 mm<br>Moisture content: < 20wt% |
| Fluidized-Bed Combustion | Fuel type: various fuels, better suited for woody biomass than herbaceous biomaterial<br>Particle type: < 80 mm (BFB), <40 mm (CFB)<br>Temperature: <900°C |
| Packed-Bed Combustion | Fuel type: wide range of fuels, including coal, peat, straw, and woody residues<br>Particle type: fairly large pieces < 30 mm |
| Cyclone Combustion | Ash content: > 6%<br>Volatiles: > 15% except in a dried form<br>Moisture content: > 20% |

Aside from the chemical characteristics of biomass, attention should be given to its physical attributes such as grindability and size. Grindability traits encompass strength, hardness, and fracture resistance. The hardgrove grindability index serves as a measure of coal's pulverization ease, where a higher value indicates easier pulverization. While coal exhibits hard but crushable physical properties, biomass generally displays tough and sturdy characteristics. This consideration is crucial, especially when employing biomass with a low hardgrove value in pulverizer-type boiler co-firing. Particle size of biomass warrants attention, particularly in co-firing operations within pulverizer-type boilers, which typically necessitate smaller particle sizes compared to other boiler types. Furthermore, conditioning the diminutive particle size of biomass during co-firing in pulverizer-type boilers will streamline the milling process.

## 2 Methods

This test was conducted at a coal-fired power plant with a 300 MW pulverized coal boiler, with coal fuel specifications having a calorific value above 4,200 kCal/kg. The selection of biomass type and percentage used in this trial was based on the biomass supply source, compatibility of biomass characteristics with the pulverized coal boiler design, and investment costs. Biomass supply sources were chosen considering transportation costs and maintaining biomass quality during delivery, with proximity to the power plant reducing transportation costs and ensuring easier quality control. Additionally, biomass supply continuity in meeting the power plant's daily operational needs was evaluated. A survey revealed a potential wood pellet supply within a <50 km radius of the power plant, estimated at around 250 tons/day, whereas the operational need for co-firing at 5% biomass assumption at full load was approximately 230 tons/day.

Compatibility of biomass characteristics with the pulverized coal boiler design was assessed based on chemical and physical characteristics. Chemical characteristics were aligned with the boiler's specifications, considering parameters such as calorific value, moisture content, chlorine content, alkali content, and ash fusion temperature. Wood biomass with a calorific value equivalent to low-rank coal or 3009-4132 kCal/kg and moisture content of 15-35% fell within the boiler design criteria. Physical characteristics, including particle size and Hardgrove Grindability Index, were also considered. Two types of wood biomass, sawdust and wood pellets, were evaluated, with particle sizes differing (approximately 2.5 mm for sawdust and 6-32 mm for wood pellets), while the boiler design required 70% weight of particles to be of 200 mesh. Wood biomass exhibited tough characteristics, making it difficult to grind, with its Hardgrove grindability index lower than the coal mill's design capability. To enable high-percentage co-firing with wood biomass, significant equipment modifications requiring substantial time and cost were necessary. Hence, direct co-firing without equipment modifications was preferred, offering the advantage of quickly implementing renewable energy blending programs with low investment costs. To meet these criteria, sawdust wood biomass was selected for co-firing at 5% without major equipment modifications.

This study aims to comprehend the characteristics of sawdust/wood powder biomass as a substitute for power plant fuel, comparing equipment performance during combustion with 100% coal fuel and a 95% coal - 5% sawdust biomass mixture, evaluating the impact of co-firing on power plant performance and exhaust gas emissions.

The testing methodology involves a comparative approach between the combustion results using a coal-biomass mixture and 100% coal fuel. The testing process stages are depicted in **Fig. 3**.

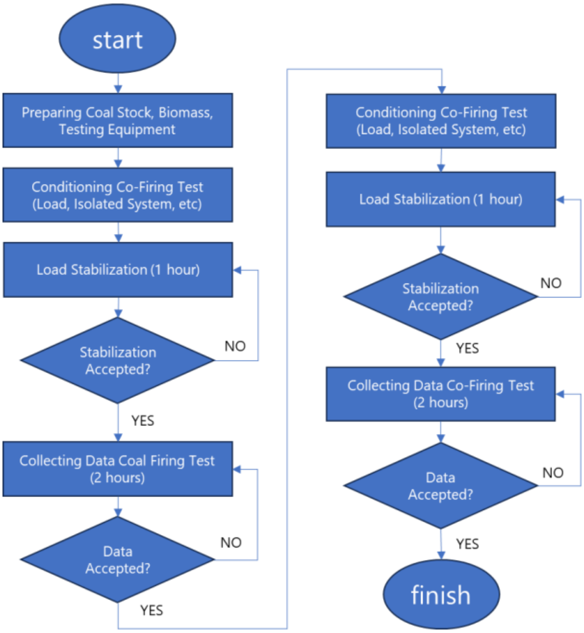


**Fig. 3.** Testing Flow Chart

Fuel preparation necessitates calculating the minimum coal and coal-biomass mixture fuel requirements for a 4-hour operation, with 1 hour allocated for load and fuel conditioning processes, 1 hour for stabilization, and 2 hours for data collection. Additionally, the testing equipment requires inspection and documentation of installed measuring devices to be utilized in the testing, along with any supplementary testing equipment if needed.

The fuel for both tests can be conditioned beforehand, ensuring quality and homogeneity through supply, storage, and mixing processes. Throughout the testing, the turbine boiler system remains in a closed cycle to maintain the testing scope.

Both tests are conducted under identical load, control settings, and conditions, each lasting for a 2-hour data collection period preceded by 1 hour of stabilization and monitoring of parameters according to applicable standards [15]. Equipment conditions and operational parameters, including mill, boiler, and steam side operations, are monitored during the tests to detect any changes resulting from blending various fuel types. Fuel samples used during the tests and residual combustion ash are collected for laboratory testing. Exhaust gas emission data are collected throughout the testing period.

The process of collecting operational parameter data using installed measuring equipment is facilitated by utilizing DCS (Data Control System) recording equipment automatically, with data retrieval intervals set at 1-minute intervals or adjusted based on instrument capabilities and data recording unit. Manual data recording at the local panel, supplementary data measurements, and in the control room can be conducted by capturing DCS screenshots every 15 minutes during the testing period.

## 3 Results and Discussion

The fuel sample testing results from the trial indicate that sawdust contains 0.01% sulfur, which is lower than the 0.1% sulfur content found in the coal used. Consequently, incorporating sawdust in the co-firing process could potentially lower SOx emissions. This approach can help in achieving the emission standards specified by the Ministry of Environment and Forestry Regulation Number 15 of 2019.

Sawdust has a higher volatile matter content compared to coal, which makes it more flammable. This is an important factor to consider during co-firing, especially for managing the mill outlet temperature. Because sawdust has more volatile matter, it ignites faster than coal, helping to speed up the combustion process in the boiler. However, sawdust has a lower Hardgrove Grindability Index (HGI) than coal, making it harder to grind.

This issue needs attention because the average HGI design for coal mills is above 45, which means that monitoring the mills/pulverizers is necessary. The sawdust used in this test has a lower calorific value of 1,943 kCal/kg compared to the coal used, which has a calorific value of 3,807 kCal/kg. The large difference in calorific values must be taken into account, especially if a high percentage of sawdust is used, as it will decrease the calorific value of the coal-sawdust mixture, potentially resulting in not meeting the targeted electricity production.

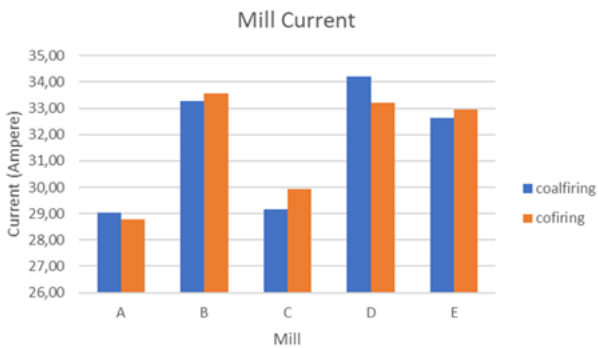


**Fig. 4.** Current (Ampere) on Each Mill for Coal Firing and Co-Firing Testing

**Fig. 4** illustrates the comparison of current levels from each operational mill. In the co-firing test, there was a marginal increase in average mill current, approximately 0.78 Amperes, compared to the coal firing operation. This rise in mill current during operation could stem from the lower grindability of sawdust compared to coal, resulting in the mill exerting more effort to grind the sawdust.

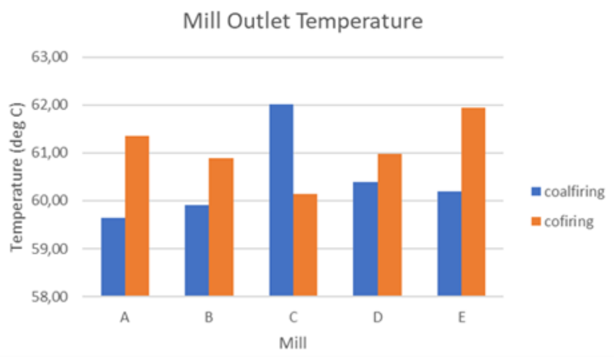


**Fig. 5.** Mill Outlet Temperature for Coal Firing and Co-Firing Testing

During the co-firing test at 5%, the average mill outlet temperature showed a tendency to rise by around 1.72°C compared to the coal firing operation. According to the data depicted in Figure 5, with the exception of mill C, most mills experienced an increase in mill outlet temperature ranging between 1-3%.

To dry the fuel in the pulverizer, hot air is directed through the air preheater by the forced draft fan. However, there is a need to be vigilant about the potential for explosions if fuel with a high volatile matter content ignites during the milling process prior to entering the boiler. This hot air is meant to dry the fuel and carry the mixture of hot air and fuel into the combustion chamber. Consequently, it is essential to constantly monitor the outlet temperature from the mill to identify any possibility of early combustion occurring inside the mill.

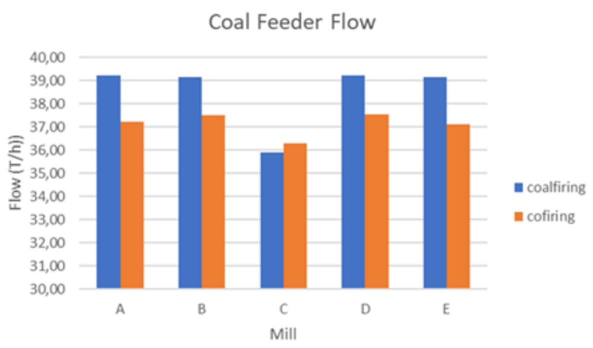


**Fig. 6.** Coal Feeders Flow on Coal Firing and Co-Firing Testing

Testing of coal firing and co-firing was conducted at a 300 MW load setting, with other operational parameters adjusted accordingly. In the co-firing trial, the percentage of sawdust substitution in the fuel mixture was determined by weight. To ascertain the fuel volume, the fuel flow rates from each operational coal feeder and the total fuel flow rate from all mills were monitored over time. **Fig. 6** illustrates the fuel flow at the coal feeders feeding into the boiler, where the total coal flow is the cumulative coal flow from all operating coal feeders. Throughout the co-firing trial, the average total coal flow was 6.37 tons per hour lower compared to the coal firing scenario. Utilizing the data on total coal flow and energy production during the trials, the specific fuel consumption (SFC) was calculated as 0.63 kg/kWh during coal firing and 0.62 kg/kWh during co-firing.

Both experiments employed coal sourced from the same origin and sawdust, which possesses a lower calorific value than the coal utilized. Ensuring coal uniformity from a single source is complex, potentially leading to variations in calorific value test outcomes for the coal at different layers. The proportion of sawdust utilized is significantly smaller compared to coal, thus the modest impact of sawdust's lower calorific value on the composite calorific value.

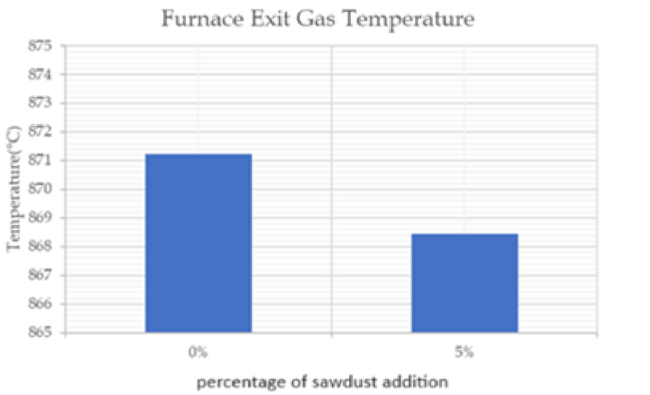


**Fig. 7.** Furnace Exit Gas Temperature on Coal Firing and Co-Firing Testing with 5% Sawdust Addition

Understanding the temperature of combustion within the boiler is crucial for grasping its combustion performance and its economic and environmental implications. The Furnace Exit Gas Temperature (FEGT) can have a significant impact on the boiler's performance and reliability. Boiler design entails balancing energy between the combustion side and the steam side. While monitoring the steam side in boilers is generally sufficient, combustion monitoring and control often fall short. The process begins with the mixing of fuel and air, followed by combustion within the furnace, with subsequent monitoring focusing on the flue gas path up to the furnace exit gas temperature. Hence, one critical control point from the burner outlet to the boiler furnace outlet is the FEGT.

The furnace outlet marks the boundary between the radiation and convection zones. FEGT serves as an indicator of the balance between heat absorption through radiation and convection. Monitoring FEGT allows observation of potential deposit formation on boiler tubes in the convection area. Exceeding the initial deformation temperature (IDT) of coal ash with FEGT can result in significant deposit buildup on boiler tubes due to molten ash. Additionally, it's crucial to monitor the flue gas temperature upon entering the superheater and reheater to ensure it remains below the ash fusion temperature (AFT).

FEGT testing is carried out using a thermo-gun at various sampling points across different furnace areas. Figure 8 illustrates the average FEGT measurements at these sampling points during the testing period, showing a reduction of 2.78°C in average FEGT during sawdust co-firing compared to coal firing. The greater volatile matter content in sawdust compared to coal results in sawdust igniting earlier.

After leaving the boiler, the heat in the flue gas is still harnessed to preheat combustion air through the air heater. The efficiency of heat absorption in the air heater may be influenced by co-firing operations, where biomass usage can impact the resulting flue gas temperature and the ash content in the biomass, typically affecting fouling levels in the air heater. One operational parameter that can be observed is the flue gas air heater temperature, both at the inlet and outlet sides. In Figure 8, it's noticeable that with sawdust co-firing, the flue gas air heater temperatures at the inlet and outlet sides are nearly identical compared to coal firing operations.

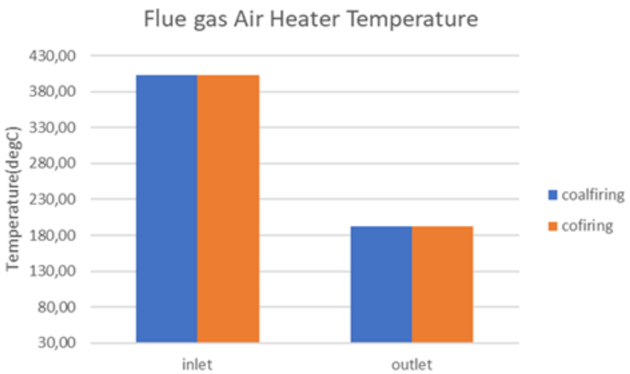


**Fig. 8.** Flue Gas Temperature on Coal Firing and Co-Firing Testing in Inlet and Outlet Air Heater

Main steam refers to superheated steam utilized for powering the high-pressure turbine, mainly sourced from the feed water flow heated within the boiler. The moisture content in the fuel impacts the rate of oxidation processes. The presence of water in the fuel affects its utilization, with elevated moisture content diminishing the calorific value of coal during combustion.

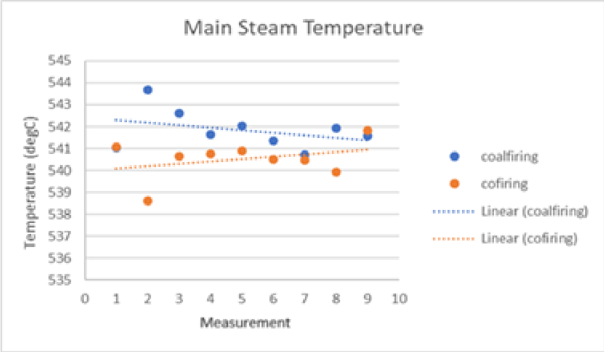


**Fig. 9.** Comparison of Main Steam Temperature in Coal Firing and Co-Firing Method

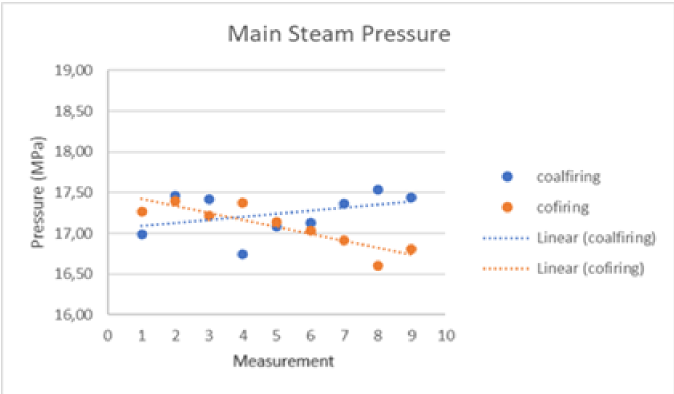


**Fig. 10.** Comparison of Main Steam Pressure in Coal Firing and Co-Firing Method

In **Fig. 9** and **Fig. 10**, there is a comparison of operational parameters for the main steam: main steam pressure and main steam temperature. At a comparable load of 300 MW gross, during co-firing, the average main steam temperature is approximately 1.32 degrees Celsius lower than during coal firing. However, the main steam pressure remains consistent at around 17 MPa for both tests.

Both coal and biomass fuels contain sulphur, nitrogen compounds, and ash. When burned in the boiler, these compounds are oxidized, leading to the formation of pollutants like $SO_2$ and NOx. This is a significant concern due to the potential environmental and health risks associated with these pollutants, especially in cases of acid rain. Additionally, an excess of particulate matter can contribute to air pollution and pose respiratory hazards to living organisms. Therefore, it's essential for co-firing processes to adhere to established emission standards. On average, the measured gas emission parameters indicate a decrease of 14.54 mg/Nm$^3$ in $SO_2$ emissions during co-firing compared to coal firing. Similarly, the measured NOx emission parameters show a decrease of 4.95 mg/Nm$^3$ during co-firing compared to coal firing. Both values remain below the environmental quality standards set by Minister of Environment Regulation No. 15 of 2019, which is 550 mg/Nm³.

Apart from utilizing sawdust biomass, there could be future trials to explore co-firing operations in pulverized coal-fired power plants by incorporating other biomass types like rice husks, wood pellets, and solid recovered fuel. These biomasses should possess physical and chemical characteristics that align with those of pulverized coal boilers.

## 4 Conclusion

Based on data processing and evaluation, the following conclusions can be drawn:

1. Sawdust contains lower sulfur content than coal, resulting in reduced combustion emissions during co-firing. Sawdust's higher volatile matter content compared to coal enhances combustion reactivity.
2. Monitoring operational parameters at a 300 MW gross load reveals that during co-firing, various parameters exhibit changes compared to coal firing. For instance, main steam temperature decreases by 1.32°C, while main steam pressure remains relatively stable. Flue gas air heater temperature and furnace exit gas temperature remain consistent, whereas mill outlet temperature increases by 1.72°C, mill current rises by 0.78 Amperes, and total coal flow decreases by 6.37 tons per hour.
3. Co-firing with sawdust leads to increased mill activity, evidenced by elevated mill current and mill outlet temperature. However, air heater performance remains unaffected, and steam production remains relatively steady.
4. Specific Fuel Consumption decreases by 0.01 kCal/kWh during co-firing compared to coal firing.

Environmental emissions experience changes during co-firing, with reductions observed in both $SO_2$ and NOx emissions compared to coal firing: $SO_2$ emissions decrease by 14.54 mg/Nm³, and NOx emissions decrease by 4.95 mg/Nm³.

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## References

1. Dewan Energi Nasional: Outlook Energi Indonesia 2022. Dewan Energi Nasional (2022).
2. Pemerintah Indonesia: Perpres 22 Tahun 2017 + Lampiran.
3. Cahyo, N., Hariyostanto, E.: An Evaluation of Co-firing Palm Kernel Shell with Coal on CFB Power Plant.
4. Cahyo, N., Alif, H. H., Aditya, I. A., Saksono, H. D.: Co-firing Characteristics of Wood Pellets on Pulverized Coal Power Plant. IOP Conference Series: Materials Science and Engineering 1098(6), 062088 (2021). doi: 10.1088/1757-899X/1098/6/062088
5. Dewan Energi Nasional: Laporan Analisis Neraca Energi Nasional. Dewan Energi Nasional (2022).

6. Primadita, D. S., Kumara, I. N. S., Ariastina, W. G.: A Review on Biomass for Electricity Generation in Indonesia. Journal of Electrical, Electronics and Informatics 4(1), 1 (2020). doi: 10.24843/jeei.2020.v04.i01.p01
7. Prakoso, S. T. A. Aji: Biomassa – Pengertian, Prinsip, Manfaat & Contoh Energi. Rimbakita. Accessed: Jun. 05, 2024. [Online]. Available: https://rimbakita.com/biomassa/
8. Beagle, E., Belmont, E.: Comparative Life Cycle Assessment of Biomass Utilization for Electricity Generation in the European Union and the United States. Energy Policy 128, 267–275 (2019). doi: 10.1016/j.enpol.2019.01.006
9. Novendianto, I. B., et al.: Investigation of the Slagging and Fouling Aspects of Co-firing Coal and Organic Refuse-Derived Fuel. Thermal Science and Engineering Progress 49 (2024). doi: 10.1016/j.tsep.2024.102447
10. Prismantoko, A., et al.: Ash Deposition Behavior During Co-combustion of Solid Recovered Fuel with Different Coals. Thermal Science and Engineering Progress 48 (2024). doi: 10.1016/j.tsep.2024.102404
11. Roni, M. S., Chowdhury, S., Mamun, S., Marufuzzaman, M., Lein, W., Johnson, S.: Biomass Co-firing Technology with Policies, Challenges, and Opportunities: A Global Review. Renewable and Sustainable Energy Reviews 78, 1089–1101 (2017). doi: 10.1016/j.rser.2017.05.023
12. Gil, M. V., Rubiera, F.: Coal and Biomass Cofiring. In: New Trends in Coal Conversion: Combustion, Gasification, Emissions, and Coking, pp. 117–140. Elsevier (2018). doi: 10.1016/B978-0-08-102201-6.00005-4
13. Xu, Y., Yang, K., Zhou, J., Zhao, G.: Coal-biomass Co-firing Power Generation Technology: Current Status, Challenges and Policy Implications. Sustainability (Switzerland) 12(9) (2020). doi: 10.3390/su12093692
14. Evaluation of Methods for Characterization of Biomass Fuels. EPRI. [Online]. Available: www.epri.com
15. ASME: Fired Steam Generators Performance Test Codes AN AMERICAN NATIONAL STANDARD. ASME (2013).