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Evaluating the Efficiency–Emission Trade-Off of Biomass Co-Firing in a Large-Scale Coal-Fired Power Plant: Evidence from Java, Indonesia

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Abstract

Background: Biomass co-firing is widely promoted as a low-cost transition strategy to reduce emissions from coal-fired power plants while maintaining the reliability of baseload electricity systems. However, its operational impact on plant efficiency remains insufficiently examined, particularly in developing countries where coal still dominates the energy mix.
Objective: This study evaluates the efficiency–emission trade-off of biomass co-firing using monthly operational data from an Indonesian coal-fired power plant over the period 2021–2025.
Methods: An Error Correction Model (ECM) is applied to analyze both short-run and long-run relationships among biomass co-firing ratio, thermal efficiency measured by Net Plant Heat Rate (NPHR), and emissions of particulate matter (PM), sulphur dioxide (SO_2), and nitrogen oxides (NO_x).
Results: The findings show that biomass co-firing significantly reduces SO_2 and PM emissions in the long run, confirming its environmental benefits. However, it also leads to a decline in thermal efficiency, indicated by an increase in NPHR as the co-firing ratio rises. In contrast, NO_x emissions are not significantly affected, suggesting they are more influenced by combustion conditions than fuel substitution. Overall, the results highlight a clear trade-off between emission reduction and efficiency performance.
Conclusion: The study concludes that although biomass co-firing supports decarbonization in coal-dependent power systems, its implementation should carefully balance environmental objectives with efficiency losses and operational reliability considerations.

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INTRODUCTION

Climate change has become one of the greatest challenges in modern global development (Tamang, 2024). The increase in greenhouse gas concentrations due to massive fossil fuel use has driven global temperature rises and increased pressure on the world's energy systems (Bilgili et al., 2024). In this context, the electricity sector is a primary concern because coal-fired power plants remain one of the largest sources of emissions, particularly in developing countries whose energy systems are still heavily dependent on fossil fuels (Shearer et al., 2017). Although the development of renewable energy continues to increase, coal still plays an important role in maintaining the stability of baseload electricity supply due to its ability to provide continuous energy at a relatively competitive cost.

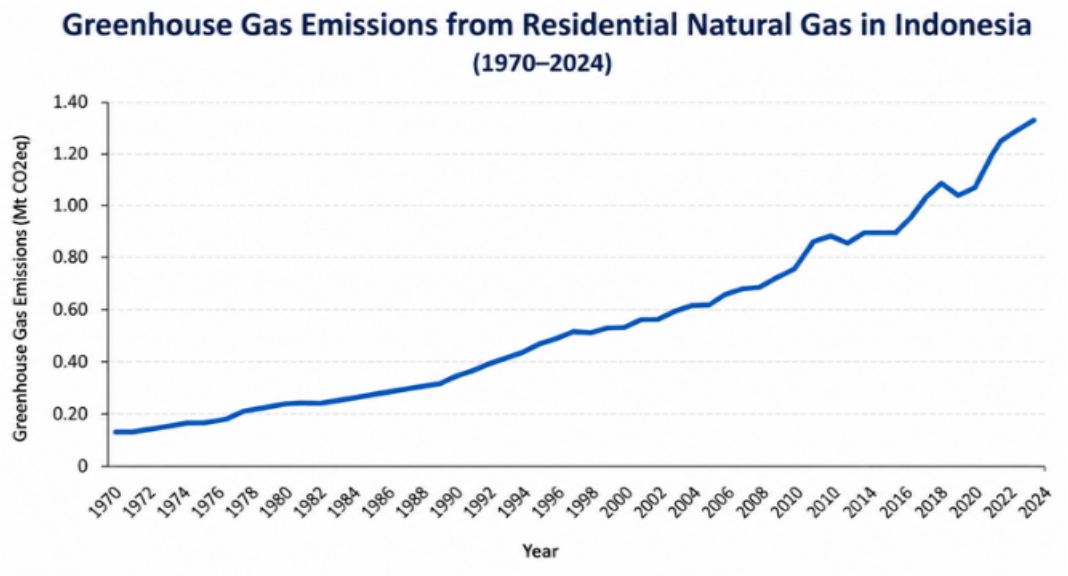

Figure 1. Trend of Indonesia's Greenhouse Gas Emissions 1970-2024 (JRC - 2025)

In Indonesia, the dominance of coal-fired power plants in the national electricity system remains very strong. Coal-based plants supply more than half of the national electricity demand and form the backbone of the Java-Bali interconnection system. However, dependence on coal also poses increasingly significant environmental challenges, particularly regarding emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), and carbon emissions that contribute to climate change and air quality degradation. This situation encourages the government and electricity industry players to seek energy transition strategies capable of reducing emissions without disrupting the reliability of the power generation system.

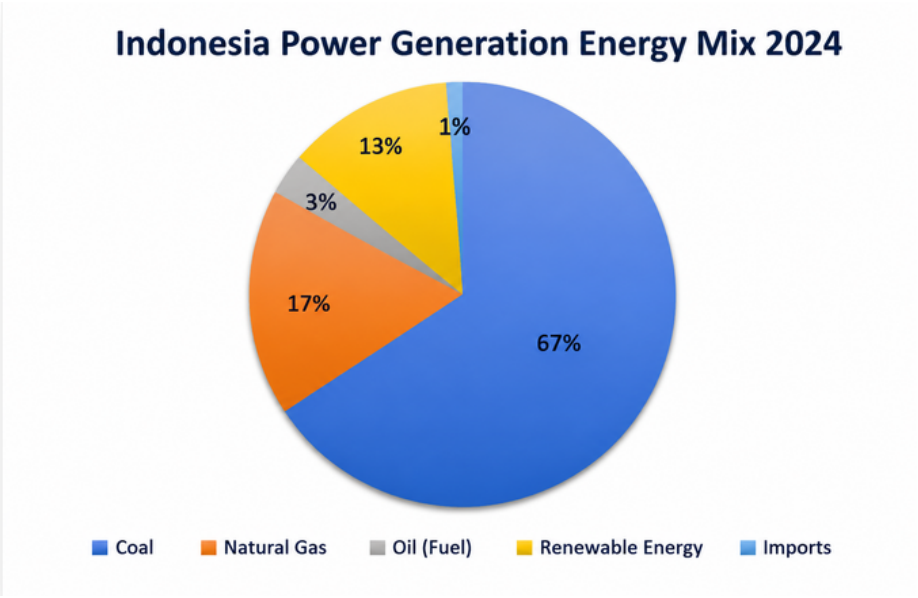

Figure 2. Indonesia's Power Generation Energy Mix for 2024.
(Ministry of Energy and Mineral Resources, 2024)

One strategy that has developed in recent years is the implementation of biomass co-firing in existing coal-fired power plants (Triani et al., 2022; Wang et al., 2025). By substituting a portion of coal with biomass, co-firing is seen as a relatively fast and economical transition approach because it can be applied without requiring major changes to plant infrastructure (Guo, 2022). Compared to building new renewable energy plants that require large investments and long development times, co-firing offers a more realistic decarbonization alternative for countries still dependent on coal plants (He et al., 2026; Smith et al., 2019). Additionally, biomass generally has

lower sulphur content than coal, thus potentially reducing certain pollutant emissions, particularly SO_2 and particulate matter.

Nevertheless, the implementation of biomass co-firing also entails non-trivial operational consequences. Biomass has different physical and chemical characteristics compared to coal, such as lower calorific value, higher moisture content, and different combustion stability. These characteristics potentially affect the plant's thermal efficiency because the plant requires greater energy input to produce the same electrical output. In practice, this condition can be reflected through changes in the Net Plant Heat Rate (NPHR), which is a key indicator of power plant efficiency. Thus, the implementation of biomass co-firing has the potential to create a trade-off between emission reduction and a decrease in plant operational efficiency.

Several previous studies have shown that biomass co-firing can reduce sulphur and particulate emissions in coal-fired power plants. Some studies also highlight the potential of co-firing to support the decarbonization targets of the energy sector with relatively low implementation costs. However, most previous research has still focused separately on either environmental aspects or technical aspects. Empirical studies that simultaneously analyze the relationship between biomass use, plant efficiency, and emission outputs based on actual operational data are still relatively limited, especially in developing countries. Furthermore, most previous studies have used technical simulation approaches or laboratory experiments, thus not fully representing the operational dynamics of plants under actual long-term conditions.

Importantly, previous findings on biomass co-firing exhibit notable contradictions. While Picciano et al. (2022) reported significant emission reductions, Mun et al. (2016) and Zhai et al. (2025) demonstrated that increasing the biomass proportion tends to decrease plant efficiency due to the lower energy quality of biomass. Conversely, Aulia Ramadhan et al. (2026) and Narputro et al. (2025) found that biomass use under certain conditions can actually improve plant operational efficiency. These contradictory findings underscore the need for an integrated empirical study that simultaneously analyzes both efficiency and emission dimensions using actual operational data, which this study aims to address.

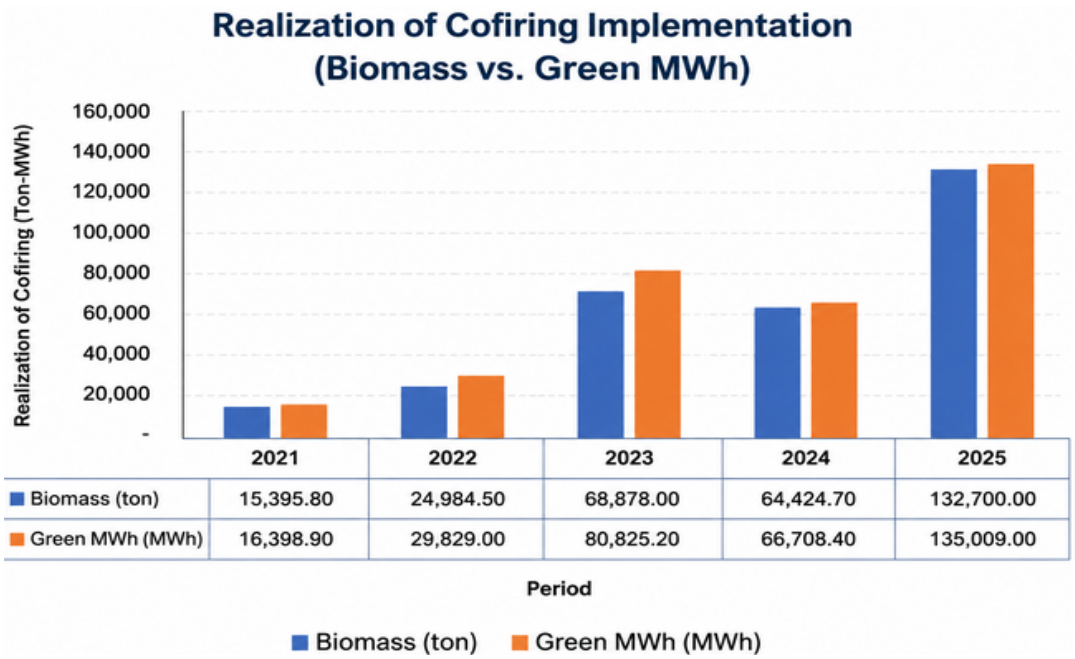

Figure 3. Realization of Co-firing at 330MW x 3 Java Coal-Fired Power Plant, 2021-2025

Based on this situation, this study aims to evaluate the efficiency-emission trade-off in the implementation of biomass co-firing at a large-scale coal-fired power plant in Java with an installed capacity of 3 × 330 MW. The research uses monthly operational data for the period 2021-2025 and applies the Error Correction Model (ECM) approach to analyze short-run and long-run relationships between biomass use, thermal efficiency proxied by Net Plant Heat Rate (NPHR), and pollutant emissions consisting of sulphur dioxide (SO_2), nitrogen oxides (NO_x), and

particulate matter (PM).

This study contributes to the energy transition literature by providing empirical evidence on the operational consequences of implementing biomass co-firing in coal-fired power plants. Specifically, this research emphasizes that the success of a decarbonization strategy is determined not only by the ability to reduce emissions but also by its ability to maintain the efficiency and reliability of the electricity generation system. Therefore, the results of this study are expected to provide input for policymakers and electricity industry players in designing energy transition strategies that better balance environmental aspects with plant operational performance.

The implementation of biomass co-firing at the 330MW x 3 Java coal-fired power plant since 2021 has shown an increase in renewable energy utilization in the power generation system. Nevertheless, the technical implications of biomass use on plant operational performance have not been fully measured empirically. Conceptually, substituting a portion of coal with biomass has the potential to reduce air pollutant emissions due to the cleaner characteristics of biomass. However, on the other hand, differences in calorific value and combustion properties of biomass can also affect plant efficiency, as reflected in changes in the Net Plant Heat Rate (NPHR).

This condition indicates a trade-off between emission reduction efforts and the potential change in plant operational efficiency that needs to be examined quantitatively based on actual data. To date, studies that integrate the relationship between biomass use, plant efficiency, and emission outputs at the operational level of coal-fired power plants remain limited, particularly in the Indonesian context.

Specifically, this study aims to: (1) analyze the effect of biomass use in the co-firing scheme on plant efficiency, measured through NPHR, at the 330MW x 3 Java coal-fired power plant during June 2021–December 2025; and (2) analyze the effect of biomass use and plant efficiency on changes in pollutant emissions, including SO_2, NO_x, and PM, at the same plant during the same period. These objectives are expected to contribute to both the academic literature on energy transition and the practical evaluation of co-firing implementation in coal-dependent electricity systems.

Academically, this research enriches the literature on biomass application in coal-fired power plants by integrating efficiency and emission analysis at the operational level. Practically, the results can inform plant managers and policymakers in evaluating co-firing strategies that balance environmental targets with operational performance and system reliability.

This study is limited to the 330MW x 3 Java coal-fired power plant, analyzing the relationship between biomass use, plant efficiency (NPHR), and emissions (SO_2, NO_x, PM) using monthly operational data from 2021–2025. The study does not address combustion engineering design, life cycle assessment, or investment feasibility analysis.

Literature Review

Biomass Co-Firing in Coal-Fired Power Plants

Biomass co-firing is increasingly being implemented as a decarbonization transition strategy in electricity systems that still depend on coal. By substituting a portion of coal with biomass, co-firing is expected to reduce emission intensity and pollution without requiring major changes to existing plant infrastructure. Compared to building entirely new renewable energy plants, co-firing is considered a more realistic and economical approach to support energy transition while maintaining the reliability of baseload electricity supply.

In Indonesia, the implementation of biomass co-firing is part of the national energy transition agenda through the utilization of renewable energy in existing coal-fired power plants. Common types of biomass used include wood pellets, sawdust, rice husks, empty fruit bunches, and refuse-derived fuel (RDF). Among these various types, sawdust is widely used because it has relatively stable availability and remains compatible with existing coal-fired power plant combustion systems.

Although it has environmental benefits, biomass has different physical and chemical characteristics compared to coal. Biomass generally has a lower calorific value, higher water content, and different combustion characteristics. These differences have the potential to affect combustion stability and operational efficiency of the plant. Thus, the implementation of biomass co-firing impacts not only environmental performance but also the technical performance of the

power plant.

Biomass Co-Firing and Emission Reduction

Various studies show that biomass co-firing can reduce emissions from coal-fired power plants. Picciano et al. (2022) found that biomass co-firing significantly reduces sulphur and particulate emissions because biomass has lower sulphur and ash content compared to coal. Similar results were also found by Liu et al. (2014), who showed that substituting a portion of coal with biomass can reduce SO_2 and NO_x emissions in coal-fired power plant combustion systems.

The environmental benefits of biomass co-firing mainly stem from the relatively cleaner chemical characteristics of biomass compared to coal. Biomass generally has lower sulphur, nitrogen, and ash mineral content, resulting in smaller emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM). Moreover, co-firing is also seen as a transitional decarbonization strategy capable of reducing emissions without reducing the reliability of the electricity system.

However, empirical results regarding emission reduction do not always show a uniform pattern, especially for NO_x emissions. Some studies indicate that NO_x formation is more influenced by combustion temperature, burner configuration, and operating conditions than by fuel composition alone. This shows that the environmental impact of co-firing implementation is highly dependent on the operational conditions and characteristics of each plant.

Biomass Co-Firing and Thermal Efficiency

In addition to impacting emissions, the implementation of biomass co-firing also has the potential to affect the thermal efficiency of power plants. Thermal efficiency is generally measured using Net Plant Heat Rate (NPHR), which is the amount of heat energy needed to produce one unit of electricity. The higher the NPHR value, the lower the plant efficiency because greater input energy is required to produce the same electrical output.

Theoretically, changes in fuel composition affect the energy conversion process in power plants. Biomass has a lower calorific value and higher moisture content compared to coal, which can increase fuel consumption and reduce combustion efficiency. Explained biomass characteristics can affect combustion stability and thermal performance of the plant during co-firing implementation.

Empirical research on the relationship between biomass co-firing and thermal efficiency still shows mixed results. Aulia Ramadhan et al. (2026) and Narputro et al. (2025) found that biomass use under certain conditions can improve plant operational efficiency. Conversely, Mun et al. (2016) and Zhai et al. (2025) showed that increasing the proportion of biomass tends to decrease plant efficiency due to the lower energy quality of biomass and increased auxiliary power requirements. These findings indicate that the operational impact of biomass co-firing is contextual and requires empirical evaluation based on actual operational data.

Research Gap

Although research on biomass co-firing has developed quite extensively, several important research gaps remain. First, most previous studies have focused separately on either emission reduction or operational efficiency aspects, while studies analyzing both aspects simultaneously are still relatively limited. Second, most previous studies still use technical simulation approaches, laboratory experiments, or optimization models, thus not fully representing plant operational dynamics under actual conditions.

Third, empirical research using time-series operational data on large-scale power plants is still relatively scarce, especially in developing countries whose electricity systems are still dominated by coal-fired power plants. Consequently, the short-run and long-run implications of implementing biomass co-firing on efficiency and emissions are not yet fully understood.

Based on this situation, this study aims to evaluate the efficiency-emission trade-off in the implementation of biomass co-firing at a large-scale coal-fired power plant in Java, Indonesia. Using monthly operational data for the 2021-2025 period and the Error Correction Model (ECM) approach, this research analyzes the relationship between biomass use, thermal efficiency proxied by Net Plant Heat Rate (NPHR), and emissions of sulphur dioxide (SO_2), nitrogen oxides

(NO_x), and particulate matter (PM) simultaneously in both the short run and long run.

METHOD

This study used a quantitative approach with a case study of a large-scale coal-fired power plant in Java with an installed capacity of 3 × 330 MW. The research object was selected based on the plant's consistent implementation of biomass co-firing since 2021, which allowed the observation of operational dynamics in both the short and long term.

The research used secondary data in the form of monthly time-series data covering the period from June 2021 to December 2025, resulting in a total of 55 monthly observations. Prior to analysis, the dataset was screened for missing values and outliers. No missing observations were identified in the operational records, and all data points were verified against CEMS calibration logs to ensure measurement reliability. The data included the proportion of biomass used in the co-firing scheme, plant efficiency represented by the Net Plant Heat Rate (NPHR), Equivalent Availability Factor (EAF), total monthly electricity production, and emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM).

Plant operational data were obtained from internal plant operation reports, while emission data were collected through the Continuous Emissions Monitoring System (CEMS). All data used in this study represented the actual operational conditions of the plant, enabling an empirical evaluation of the relationships between biomass utilization, operational efficiency, and emission outputs.

This study employed two main groups of variables: plant efficiency variables and emission variables. Plant efficiency was represented by the Net Plant Heat Rate (NPHR), while the emission variables consisted of sulphur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM). The primary independent variable in this study was the proportion of biomass used in the co-firing scheme.

Additionally, the research included control variables such as the Equivalent Availability Factor (EAF) and total electricity production (Total GWh) to represent plant operational conditions. These variables were incorporated to reduce the potential for omitted variable bias in the estimation model.

Table 1. Operational Definition of Variables and Measurement Units

Variable	Operational Definition	Unit
CoFiring	Proportion of biomass to total fuel energy input	%
NPHR	Heat energy required to produce 1 kWh of electricity	kcal/kWh
SO_2	Total monthly sulphur dioxide emissions	Kg
NO_x	Total monthly nitrogen oxides emissions	Kg
PM	Total monthly particulate matter emissions	Kg
EAF	Plant unit availability rate	%
GWh Total	Total monthly electricity production	GWh

This study used the Error Correction Model (ECM) approach to analyze the short-run and long-run relationships between biomass use, plant efficiency, and emissions. The ECM approach was chosen because the implementation of biomass co-firing had the potential to cause dynamic operational changes in both the short and long term.

The initial stage involved estimating the long-run relationship using the Ordinary Least Squares (OLS) method. The first model was used to analyze the effect of biomass use on plant efficiency, which was proxied by NPHR, using the following equation:

$$NPHR_t = \beta_0 + \beta_1 CoFiring_t + \beta_2 EAF_t + \beta_3 GWhTot_t + \varepsilon_t$$

Furthermore, the second model was used to analyze the effect of biomass use and plant efficiency on emissions:

$$EM_t = \beta_0 + \beta_1 CoFiring_t + \beta_2 NPHR_t + \beta_3 EAF_t + \beta_4 GWhTot_t + \varepsilon_t$$

where EM_t represents emissions of SO_2, NO_x, or PM.

To capture short-run dynamics and the adjustment mechanism towards long-run equilibrium, the ECM model is as follows:

$$\Delta EM_t = \alpha_0 + \alpha_1 \Delta CoFiring_t + \alpha_2 \Delta NPHR_t + \alpha_3 \Delta EAF_t + \alpha_4 \Delta GWhTot_t + \lambda ECT_{t-1} + \mu_t$$

The coefficient ECT_{t-1} represents the error correction term, which indicates the speed of adjustment towards long-run equilibrium. A negative and significant coefficient value indicates that the system has a correction mechanism for short-run deviations.

The analysis began with stationarity testing using the Augmented Dickey-Fuller (ADF) test to ensure that the variables did not contain a unit root. Variables that were not stationary at the level but became stationary at the first difference were categorized as integrated of order one [I(1)].

Next, cointegration testing was performed using the Engle-Granger two-step method to identify the existence of long-run relationships among variables. The Engle-Granger approach was selected over the Johansen Cointegration Test because each model in this study specified a single-equation framework with one dependent variable and multiple independent variables, rather than a system of simultaneous endogenous equations. In single-equation contexts with a clearly defined dependent variable, the Engle-Granger method provided a parsimonious and statistically sufficient framework for testing cointegration (Engle & Granger, 2015). If the residuals from the long-run estimation were proven to be stationary, the variables were declared cointegrated, allowing the ECM model to be applied.

After the ECM model was estimated, statistical testing was conducted using t-tests and F-tests to evaluate the significance of the model parameters. Additionally, the research performed classical assumption tests, including normality, heteroscedasticity, autocorrelation, and multicollinearity tests, to ensure the validity of the econometric model used. The results of all classical assumption tests were presented in the results section to demonstrate that the estimated models satisfied the requirements for Best Linear Unbiased Estimation (BLUE).

RESULTS AND DISCUSSION

Results

Operational Characteristics and Dynamics of Co-Firing Implementation

This study uses a large-scale coal-fired power plant in Java with an installed capacity of 3 × 330 MW as its study object. This plant operates as a baseload unit in the Java-Bali interconnection system, thus having relatively stable operational characteristics, high utilization rates, and continuous electricity production patterns. These characteristics make this plant relevant for evaluating the operational implications of implementing biomass co-firing on efficiency and emissions over a long-term horizon.

Since 2021, the plant began commercially implementing biomass co-firing, utilizing sawdust as a partial coal substitution fuel. Over its development, biomass use has shown a significant increasing trend year by year, both in terms of biomass volume and biomass-based electricity production (green electricity). This increase indicates that co-firing is no longer just a pilot project but has become a sustainable part of the plant's operational system.

However, the increasing intensity of co-firing also brings non-trivial technical implications. Biomass has different energy characteristics compared to coal, particularly in terms of calorific value, moisture content, and combustion stability. These characteristic differences have the potential to affect the plant's thermal performance, fuel consumption, and emission formation patterns during the combustion process. Thus, the implementation of co-firing is not only an environmental issue but also an issue of plant operation efficiency and stability.

Descriptive Statistics

Descriptive statistics are used to provide an initial overview of the characteristics of the operational data used in the study. The variables analyzed include emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), co-firing proportion, Net Plant Heat Rate (NPHR), Equivalent Availability Factor (EAF), and total monthly electricity production. Table 2

presents the summary statistics including minimum, maximum, mean, and standard deviation for all study variables.

The descriptive statistics results show that the emission variables have a relatively high degree of variation, indicating that the plant's environmental performance is influenced by a combination of operational factors and fuel composition. The co-firing variable has an average value of 1.16% with a maximum value reaching 3.31%, indicating that biomass implementation has been carried out gradually and fluctuated during the observation period. This variation not only reflects the dynamics of plant operations but also shows that the success of co-firing implementation is still heavily influenced by the stability of the biomass supply chain.

From an efficiency perspective, the average NPHR value of 2928.27 kcal/kWh indicates that the plant's thermal performance was dynamic during the research period. In the context of power plant operations, an increase in NPHR value indicates a decrease in efficiency because the plant requires greater energy input to produce the same electrical output. This condition is important because it shows that changes in fuel composition have the potential to directly affect the plant's technical performance.

Meanwhile, the relatively high EAF value indicates that the plant operates continuously, close to full load conditions. This strengthens the validity of the research because the observed data variation more represents changes in the plant's internal conditions rather than extreme external operational disturbances.

Overall, the descriptive statistics show that the research data has adequate variation to be analyzed using time-series econometric approaches. Furthermore, the pattern of variation among variables also begins to indicate a complex relationship between biomass use, thermal efficiency, and plant emissions.

Stationarity and Cointegration Tests

Before estimating the model, this study first conducted stationarity testing using the Augmented Dickey-Fuller (ADF) method to ensure that the time-series data would not produce spurious regression. The test results show that the emission variables (SO_2, NO_x, and PM), EAF, and total electricity production are stationary at the level or integrated of order zero [I(0)]. Meanwhile, the co-firing and NPHR variables only became stationary after first differencing, thus being integrated of order one [I(1)].

The presence of a combination of I(0) and I(1) variables indicates that the relationships among variables can still be further analyzed using the Error Correction Model (ECM) approach, as long as cointegration relationships exist in the model. Therefore, the research continued testing using the Engle-Granger two-step method.

The cointegration test results showed that all models had stationary residuals with probability values below the 5 percent significance level. This finding indicates the existence of a long-run equilibrium relationship between biomass use, plant efficiency, and emissions. Thus, operational changes resulting from co-firing implementation are not merely temporary but have structural implications for the plant's technical and environmental performance in the long run.

Impact of Co-Firing on Plant Efficiency

The ECM estimation results show that the implementation of biomass co-firing yields different implications in the short run versus the long run for plant efficiency. In the short run, the co-firing variable did not show a significant effect on changes in NPHR. This finding indicates that the plant's operating system was still able to absorb changes in fuel composition without causing statistically visible efficiency disturbances immediately.

Long-Run OLS and Short-Run ECM Estimation Results (coefficients, standard errors, t-statistics, p-values, R^2, adjusted R^2, F-statistic, and ECT coefficient) for NPHR, SO_2, NO_x, and PM models — to be inserted by the author based on EViews output]

However, in the long run, co-firing proved to significantly increase the NPHR value. Since an increase in NPHR represents a decrease in thermal efficiency, this result shows that the use of biomass in the long run tends to reduce plant efficiency.

Technically, these findings can be explained by the characteristics of biomass, which has a lower calorific value and higher moisture content compared to coal. Consequently, part of the

combustion energy is used for the water evaporation process, reducing the net energy that can be converted into electricity. Additionally, the different combustion characteristics between biomass and coal also have the potential to affect flame stability, heat transfer efficiency, and overall boiler performance.

This finding indicates that the implementation of co-firing cannot be understood solely as an emission reduction strategy, but also as a change in the energy input structure that carries consequences for the productivity of the generation system. In other words, the emission reductions achieved through biomass substitution may be paid for by a decrease in the plant's thermal efficiency.

Discussion

Impact of Co-Firing on Emissions

SO_2 Emissions

The estimation results show that biomass co-firing has a negative and significant effect on SO_2 emissions in both the short run and long run. This finding confirms that biomass is effective in reducing sulphur emissions because it has much lower sulphur content than coal. Thus, substituting a portion of coal with biomass directly reduces the main source of sulphur dioxide formation during the combustion process.

Interestingly, the NPHR variable shows a positive effect on SO_2 emissions in the long run. This indicates that a decrease in plant efficiency tends to increase sulphur emissions due to increased fuel consumption to produce the same electrical output. This finding shows that environmental performance and technical performance of the plant are interrelated and cannot be separated partially.

NO_x Emissions

Unlike SO_2, the estimation results show that co-firing does not have a significant effect on NO_x emissions. Even all operational variables in the model also did not show statistically significant relationships. This finding can be explained by the three primary mechanisms of NO_x formation in coal combustion. Thermal NO_x, the dominant pathway, is formed through the oxidation of atmospheric nitrogen at temperatures exceeding 1,500°C (Zeldovich mechanism) and is primarily governed by flame temperature and residence time rather than fuel type.

Fuel NO_x originates from the oxidation of nitrogen chemically bound in the fuel; since both coal and biomass contain nitrogen compounds, substituting a portion of coal with biomass does not substantially alter the total fuel-bound nitrogen available for conversion. Prompt NO_x, formed through hydrocarbon radical reactions in fuel-rich zones, is also largely independent of fuel composition changes at the co-firing ratios employed in this study. Consequently, the combustion temperature profile, air-fuel ratio, and burner configuration remain the dominant determinants of NO_x formation, explaining why changes in fuel composition through co-firing do not produce a statistically significant effect on NO_x emissions.

This result is important because it shows that the effectiveness of co-firing as an emission control instrument is selective. Not all types of pollutants respond to changes in fuel composition in the same pattern. Therefore, NO_x control requires additional technical approaches such as combustion optimization or the application of low-NOx burner and Selective Catalytic Reduction (SCR) technologies.

PM Emissions

For particulate matter (PM) emissions, the estimation results show that co-firing has a negative and significant effect in the long run, although not significant in the short run. This finding indicates that the reduction in particulate emissions due to biomass use requires an operational adjustment process before its full impact is seen.

The reduction in PM can be explained by the characteristic of biomass having lower ash content than coal. However, the research results also show that increases in NPHR and electricity production actually increase PM emissions significantly. Thus, the effectiveness of co-firing in reducing particulates is strongly influenced by the plant's ability to maintain efficiency and operational stability.

Synthesis of the Efficiency-Emission Trade-Off

Overall, the results of this study indicate that the implementation of biomass co-firing produces a paradoxical relationship between decarbonization goals and the operational performance of power plants. On one hand, co-firing is proven capable of reducing emissions of sulphur dioxide (SO_2) and particulate matter (PM), demonstrating that biomass substitution provides environmental benefits in the form of reducing sulphur-based and particulate pollutants. On the other hand, an increase in the proportion of biomass actually increases the Net Plant Heat Rate (NPHR) value, which indicates a decrease in the plant's long-term thermal efficiency.

From a theoretical perspective, these findings can be interpreted through the lens of Environmental Economics and the theory of externalities (Baumol & Oates, 1988; Pigou & Aslanbeigui, 2017). The efficiency–emission trade-off observed in this study exemplifies the concept of abatement costs, wherein emission reductions are not achieved without sacrificing other dimensions of economic performance. Furthermore, the findings align with the Sustainable Energy Management framework, which emphasizes that energy transition strategies must simultaneously optimize environmental, technical, and economic outcomes rather than pursuing singular emission reduction targets. The selective effectiveness of co-firing across emission types also resonates with the Energy Transition Theory, which posits that the pathway from fossil-dependent to cleaner energy systems involves complex trade-offs that require adaptive policy instruments and technology-specific interventions (Bhattacharyya, 2011).

These findings confirm that the implementation of co-firing does not entirely represent a costless energy transition. In operational practice, the environmental benefits obtained through emission reductions are accompanied by the consequence of increased energy input requirements to produce the same electrical output. In other words, electricity generation becomes cleaner, but at the same time becomes less thermally efficient. This condition indicates the existence of a real and structural efficiency-emission trade-off in the implementation of biomass co-firing in coal-fired power plants.

Furthermore, the results show that the emission reductions generated by co-firing are not yet fully proportional to the efficiency decline consequences it causes. Although SO_2 and PM emissions decrease, biomass implementation also increases primary energy consumption due to the biomass's low calorific value and high moisture content. From an energy economics perspective, this condition can create hidden operational costs in the form of increased fuel consumption, decreased combustion efficiency, increased boiler operation load, and potential increases in the long-term cost of electricity production.

Critically, these findings indicate that the success of co-firing cannot be measured solely by its ability to reduce emissions. An energy transition approach that is too oriented towards emission reduction indicators risks ignoring the dimensions of system efficiency and energy productivity. In the context of coal-fired power plants that remain the backbone of electricity systems in developing countries, a decrease in thermal efficiency can have broader implications for national energy consumption, fuel supply needs, and overall electricity generation costs.

Moreover, the results also show that the effectiveness of co-firing as a decarbonization instrument is selective among emission types. Significant reductions only occur for SO_2 and PM emissions, while NO_x emissions do not show statistically significant changes. This indicates that biomass substitution does not automatically improve all dimensions of the plant's environmental performance. Thus, the narrative that co-firing always results in a cleaner generation system needs to be understood more carefully and contextually.

These findings are consistent with recent international studies. Chen et al. (2025) reported similar efficiency–emission trade-offs in a Chinese coal-fired power plant co-firing papermaking biomass, where emission reductions were accompanied by operational efficiency fluctuations. Setiawan et al. (2024) found that optimizing biomass supply chains in West Java could mitigate environmental impacts but required careful balancing of logistical and technical constraints. Zhai et al. (2025) demonstrated that biomass co-firing contributes to emission reductions and employment in coal regions, yet acknowledged the thermal efficiency penalty as a persistent challenge. These international comparisons reinforce the finding that the efficiency–emission trade-off is a structural feature of biomass co-firing rather than a context-specific

anomaly.

Nevertheless, this study does not suggest that co-firing is a failed strategy. On the contrary, the results confirm that the implementation of co-firing requires a more comprehensive optimization approach. Empirical findings indicate that increasing electricity output under stable operating conditions can still improve efficiency through economies of scale mechanisms. This means that the negative impact of biomass on efficiency can still be minimized through controlling biomass quality, optimizing fuel mixing ratios, stabilizing combustion processes, and increasing plant operational flexibility.

In the context of energy transition, the results of this study provide an important critique of decarbonization approaches that overemphasize environmental aspects without considering overall energy system performance. The transition to cleaner energy is not always synonymous with improved energy efficiency. In some cases, emission reductions are actually achieved at the expense of operational efficiency and increased primary energy consumption. Therefore, biomass co-firing policies need to be evaluated not only based on emission reduction targets but also based on the ability to maintain plant efficiency, electricity system stability, and the long-term economic sustainability of plant operations.

Thus, this study demonstrates that the main challenge of implementing biomass co-firing is not merely how to reduce emissions, but how to manage the simultaneous compromise between environmental performance and operational efficiency. This perspective becomes very important for developing countries that still depend on coal-fired power plants as their main source of national electricity, where the success of the energy transition must still consider aspects of system reliability, energy costs, and overall generation productivity.

CONCLUSION

This study evaluates the efficiency-emission trade-off in the implementation of biomass co-firing at a large-scale coal-fired power plant in Java using the Error Correction Model (ECM) approach and monthly operational data for the 2021-2025 period. The results show that biomass co-firing significantly reduces emissions of sulphur dioxide (SO_2) and particulate matter (PM), thus supporting its role as an energy transition strategy to reduce the environmental impact of coal-based electricity generation. However, biomass implementation is also proven to increase the Net Plant Heat Rate (NPHR) in the long run, indicating a decrease in the plant's thermal efficiency.

These findings confirm that the implementation of co-firing does not simultaneously produce operational and environmental benefits. The emission reductions achieved through biomass substitution are accompanied by the consequence of increased energy input requirements and decreased plant efficiency. Thus, biomass-based energy transition in coal-fired power plants cannot be understood as a costless decarbonization process, but rather as a form of compromise between environmental performance and operational performance of the plant.

Furthermore, this study also shows that the effectiveness of co-firing is selective among emission types. Although SO_2 and PM emissions decreased significantly, the effect on NO_x emissions was not proven to be statistically significant. This result indicates that changes in fuel composition are not always able to improve all dimensions of the plant's environmental performance, especially for emissions that are more influenced by combustion characteristics and system operational parameters.

From an energy economics perspective, the results of this study provide important implications that energy transition policies should not only focus on emission reduction targets. Emission reductions that are not balanced with efficiency management have the potential to create increased primary energy consumption, decreased generation productivity, and pressure on plant operating costs in the long run. Therefore, the implementation of biomass co-firing requires a more integrated approach through controlling biomass quality, optimizing fuel mixing ratios, improving combustion stability, and strengthening overall plant operational efficiency.

More broadly, this study shows that the main challenge of energy transition in developing countries is not only how to generate cleaner electricity but also how to simultaneously maintain efficiency, reliability, and sustainability of the energy system. In the context of an electricity system that still depends on coal-fired power plants as the main source of national electricity, the

success of a decarbonization strategy must be evaluated not only based on environmental indicators but also based on the ability to maintain operational performance and long-term energy resilience.

For policymakers, these findings suggest that biomass co-firing regulations should incorporate efficiency performance standards alongside emission reduction targets, ensuring that the transition to cleaner generation does not compromise system reliability. Future research is recommended to extend this analysis using multi-plant panel data and Panel ECM or ARDL approaches to improve generalizability across different plant capacities and operational contexts. Additionally, incorporating biomass quality parameters (calorific value, moisture content) and coal characteristics as moderating variables would provide deeper insights into the conditions under which co-firing can achieve optimal emission reductions with minimal efficiency losses.

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AUTHOR CONTRIBUTION STATEMENT

Z.U.N.A.H. and N.A.H. jointly contributed to the conceptualization, data collection, and methodology design of this study. Z.U.N.A.H. led the development of the econometric model, performed the formal analysis, and prepared the initial manuscript draft. N.A.H. contributed to data validation, result interpretation, and critical revision of the manuscript. Both authors reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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