Quantification of CO_2 Emission Reductions from Biomass Co-firing at a Coal-Fired Power Plant Using the IPCC 2006 Tier 2 Methodology

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Coal-fired power plants are the dominant source of electricity in Indonesia but also a major contributor to greenhouse gas (GHG) emissions, posing challenges to the country's net-zero emission commitment by 2060. This study aims to quantify the impact of biomass co-firing on emission reduction and carbon credit potential in Pangkalan Susu, Kabupaten Langkat, North Sumatra Power Plant using the 2006 IPCC Guidelines (Tier 2). Operational data from 2022 (100% coal) and 2024 (coal–biomass mix) were analyzed through a mass and energy balance approach. Results indicate that integrating 41,324 tons of solid biomass and 3,798 kiloliters of liquid biomass in 2024 reduced coal consumption by 24,379 tons and cut CO_2 emissions by 38,419 tons compared to the 2022 baseline. Although the substitution rate was only 1.72% of the fuel mix, the reduction was measurable and economically significant, providing potential carbon credit value. These findings highlight biomass co-firing as a viable strategy to reduce GHG emissions and support Indonesia's energy transition, while emphasizing the need for advanced methodologies (Tier 3, LCA) and sustainable biomass supply chains to ensure long-term implementation.
Keywords: Biomass Co-Firing, Coal-Fired Power Plant, CO_2 Emission, IPCC 2006, Carbon Credit

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1. Introduction

Carbon emissions from power generation, particularly coal-fired power plants and natural gas combined cycle systems, represent one of the main sources of anthropogenic greenhouse gases and constitute a significant contributor to global climate change (Otitoju et al., 2021; Wu Q et al., 2023). These emissions accelerate global warming by trapping heat in the atmosphere, resulting in widespread environmental and socio-economic impacts. Although various technological innovations, such as carbon capture and sequestration, renewable energy integration, and co-firing with low-carbon fuels, have demonstrated mitigation potential (Zantye et al., 2021; Hussein, S., 2025), the electricity sector continues to contribute a large share of global carbon dioxide emissions, particularly in countries that are highly dependent on coal. For example, in China the power sector contributes approximately 44 percent of national carbon dioxide emissions, highlighting the urgency of accurate emission quantification and effective reduction strategies (Wu Q et al., 2023).

Nevertheless, several challenges continue to constrain decarbonization efforts in the energy sector. Limitations in the scale and economic feasibility of carbon capture technologies (Shirizadeh et al., 2021; Wang, P. et al., 2021), along with the continued dominance of fossil fuel use in many countries, have resulted in emission reduction rates that remain inadequate. In addition, inconsistent emission assessments hinder the effectiveness of carbon pricing mechanisms and emissions trading schemes, which play an important role in promoting emission efficiency through economic incentives (Heinisch, K. et al., 2021; Yang, L. et al., 2021). Without precise emission data, governments and industries face difficulties in designing fair regulations, evaluating the effectiveness of mitigation policies, and ensuring compliance with international climate agreements such as the Paris Agreement.

Beyond technical and emission policy aspects, the renewable energy sector plays a strategic role in strengthening low-carbon energy systems. For instance, Darmana et al. (2024) examined the implementation of a Fuel Save Controller system in a hybrid energy system combining solar, wind, and diesel on Wangi-Wangi Island, Wakatobi, with the aim of optimizing fuel use and reducing generator operational emissions (T. Darmana et al., 2024). The Fuel Save Controller system regulates generator load to improve efficiency when integrated with renewable resources, thereby reducing fuel consumption and carbon dioxide emissions (T. Darmana et al., 2024). Furthermore, Darmana et al. (2024) also investigated the installation of solar panels in Wangi-Wangi to assess the technical and financial feasibility of solar energy as an additional clean power source (T. Darmana et al., 2024).

Based on these conditions and challenges, this study aims to quantify carbon emissions from coal-fired power plants using the IPCC 2006 Guidelines for National Greenhouse Gas Inventories as the methodological framework. The application of these guidelines is expected to produce transparent and reliable emission data to support national energy policy formulation, strengthen emission reduction strategies, and ensure compliance with global climate targets.

Although many studies have examined the potential of carbon capture technologies, renewable energy integration, and emission reduction policy instruments (Nicholas, T. et al., 2021; Zhao, S. et al., 2022; Ge, P. et al., 2022), empirical studies that specifically apply standardized IPCC methodologies to calculate emissions from coal-fired power plants remain limited, particularly in developing countries. Most existing research focuses more on technological or policy pathways without giving sufficient attention to methodological rigor and comparability of emission estimates across regions. This limitation creates gaps in ensuring consistency, transparency, and credibility in emission reporting.

The novelty of this research lies in the application of the IPCC 2006 Guidelines as a standardized and transparent instrument for calculating carbon dioxide emissions from coal-fired power plants, particularly in regions where similar studies are still scarce. Unlike previous research that tends to focus on technological mitigation or energy integration aspects, this study emphasizes the importance of a strong methodological foundation in emission calculation as a prerequisite for effective reduction policy design. By linking emission quantification with policy frameworks, this research is expected to provide both scientific contributions and practical support for decision-making in the energy transition. The results are expected to serve as an important reference for policymakers in designing carbon reduction strategies that balance environmental objectives, economic growth, and energy security.

The main novelty of this study lies in the integration of emission calculations based on the IPCC 2006 Tier 2 approach with actual operational data from biomass co-firing at four large-scale coal-fired power plant units in Indonesia, resulting in more representative estimates compared to previous studies that generally relied only on simulation data or default factors without empirical verification. In addition, this study specifically incorporates two types of biomass, namely solid biomass in the form of palm shell and liquid biomass in the form of crude palm oil, which are rarely analyzed simultaneously in the context of coal-fired power plants, and evaluates their impacts on emission intensity reduction and potential carbon credits within the framework of Indonesia's carbon economic value. This approach not only enriches emission quantification methodologies for fossil-based power generation but also provides a strong scientific foundation for the development of national co-firing strategies, optimization of biomass selection based on thermochemical characteristics, and technical-economic integration with carbon trading mechanisms. Accordingly, this research offers a significant new contribution to scientific and technological advancement in power generation decarbonization and the strengthening of low-carbon energy policy instruments in Indonesia.

2. Methods

Carbon Emission Calculation Method

The method for calculating carbon emissions in this study is motivated by the need to quantify the contribution of coal-fired power plants to CO_2 emissions in a transparent, consistent, and verifiable manner. Accordingly, this study adopts the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which are internationally recognized as the standard methodology for greenhouse gas (GHG) inventory development (Intergovernmental Panel on Climate Change, 2006). By applying a tiered approach (Tier 1 to Tier 3), this method allows the use of default emission factors when local data are limited, while also enabling the incorporation of plant-specific data, when available, to improve the accuracy of emission estimates.

Within this framework, the study follows a series of systematic steps, including the collection of operational and fuel characteristic data, determination of appropriate emission factors, mathematical calculation of CO_2 emissions, analysis of results including uncertainty considerations, and preparation of reports that comply with the principles of transparency and consistency across GHG inventory components. This approach not only ensures that emission estimates are scientifically accountable but also facilitates a clear interpretation of policy implications related to emission mitigation in the electricity sector. The stages involved in carbon emission calculation are described as follows.

1. IPCC 2006 Methodological Framework

The calculation of carbon emissions from coal-fired power plants in this study refers to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change, 2006). These guidelines provide a comprehensive framework emphasizing consistency, transparency, and completeness in GHG emission reporting.

The IPCC methodology employs a tiered approach based on data availability and quality:

a. Tier 1 utilizes IPCC default emission factors and is suitable when plant-specific data are limited.
b. Tier 2 and Tier 3 encourage the use of local data, including fuel characteristics, combustion technology, and power plant efficiency, to enhance estimation accuracy (Wu et al., 2023; Zhao et al., 2023).

2. Data Collection

Data collection was conducted systematically to ensure the accuracy of emission calculations. The collected data include:

a. Fuel Consumption: the amount of coal used, expressed in tons or energy equivalents (MJ).
b. Coal Characteristics: carbon content and calorific value, which vary across coal types (Prajapati et al., 2022).
c. Operational Data: electricity generation (MWh), operating hours, and plant load factor (Heinisch et al., 2021).

3. Determination of Emission Factors

Emission factors are used to convert fuel consumption into estimated CO_2 emissions.

a. When available, country-specific or plant-specific emission factors based on laboratory testing are applied to improve accuracy.
b. In the absence of specific data, default emission factors provided by the IPCC 2006 Guidelines are used (Intergovernmental Panel on Climate Change, 2006).

4. Carbon Emission Calculation

Based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy, carbon emissions are calculated using the following equation:

$$E_{CO_2} = FC_{Coal} \times EF \qquad (1)$$

where E_{CO_2}represents CO_2 emissions (tons), FCdenotes fuel consumption (tons or terajoules), and $EF$is the emission factor (tons CO_2/TJ). For bituminous coal, the default IPCC emission factor is 96.1 tCO_2/TJ (Tong et al., 2023; Zhang et al., 2023).

When an energy-based approach is applied, emissions are calculated as:

$$E_{CO_2} = Fuel\_Consumption \times NCV \times EF_{CO_2} \times FO \qquad (2)$$

where:

Fuel_Consumption	= coal consumption in year *i* (tons)
NCV	= Net Calorific Value (MJ/kg)
EF_{CO₂}	= CO_2 emission factor
FO	= national oxidation factor (0.98)

3. Results And Discussion

Operational Data and Data Sources

The data used in this study include coal consumption, thermal efficiency, calorific value, and fuel composition at the Pangkalan Susu coal-fired power plant, Langkat Regency, North Sumatra, for the year 2022 as the baseline with coal-only operation and for the year 2024 with biomass co-firing implementation. The data were obtained from the Operational Reports of Units 1 through 4. In addition, emission factors from the IPCC and adjustment factors reflecting Indonesian conditions were applied (Luo H et al., 2022; Hou H et al., 2023). To improve accuracy, this study presents the basic characteristics of the coal and biomass used as inputs for the emission calculations. Table 1 shows a comparison of calorific value, moisture content, ash content, and sulfur content between coal and biomass.

Table 1. Comparison of Coal and Biomass Characteristics

Parameter	Bituminous Coal	Solid Biomass (Palm Shell)	Liquid Biomass (CPO)
Calorific Value (HHV, MJ/kg)	23–25	15–18	28–32
Moisture Content (%)	8–12	20–40	<1
Ash Content (%)	5–10	2–5	<0.5
Sulfur Content (%)	0.6–1.2	<0.1	<0.05

The biomass data indicate significant differences compared to coal, particularly in moisture content and calorific value, which affect combustion efficiency and emission intensity. Emission and efficiency models were developed using a mass and energy balance approach to estimate carbon dioxide output under two scenarios: the baseline condition with coal-only operation and the co-firing condition. This modeling framework quantifies the emission reductions achieved through biomass integration. The empirical results are presented in the following section, highlighting operational performance comparisons and the magnitude of emission reductions.

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Table 2. Coal Consumption in 2022 (tons)

Month	Unit 1	Unit 2	Unit 3	Unit 4
January	64,913.03	65,972.68	65,988.18	66,652.30
February	62,181.59	64,765.49	64,929.07	30,345.17
March	71,702.07	56,678.86	78,338.14	45,252.36
April	65,436.05	50,148.19	91,228.59	79,190.02
May	73,568.08	23,206.32	90,817.01	82,564.37
June	43,906.41	71,696.39	72,099.29	74,912.04
July	72,862.03	79,530.93	70,538.51	73,445.97
August	79,368.07	76,700.90	70,270.90	86,467.90
September	65,888.19	74,998.28	37,633.70	72,992.20
October	37,715.42	35,410.83	56,755.92	49,461.10
Total	637,540.94	599,108.88	698,599.29	661,282.43
Grand Total	2,596,532.55			

The coal consumption profile in 2022 shows a total usage of 2,596,532.55 tons distributed across four generating units. Unit 3 recorded the highest consumption at 698,599.29 tons, while Unit 2 had the lowest consumption at 599,108.88 tons. Monthly consumption patterns exhibit considerable fluctuations. For example, in May, Units 1 and 3 reached peak consumption levels exceeding 90,000 tons, whereas Unit 2 recorded only 23,206.32 tons. These variations indicate operational adjustments, likely influenced by maintenance schedules and changes in electricity demand. The year 2022 is used as the baseline condition, assuming one hundred percent coal consumption.

Table 3. Coal Consumption in 2024 (tons)

Month	Unit 1	Unit 2	Unit 3	Unit 4
January	75,434.28	68,783.84	76,909.80	76,109.40
February	69,551.13	70,473.76	77,228.20	75,453.10
March	63,059.63	74,256.70	77,888.10	70,245.40
April	71,388.11	63,579.33	70,378.50	22,889.50
May	70,731.72	63,785.26	70,723.45	–
June	19,618.94	70,052.30	68,143.30	47,753.70
July	29,011.93	68,068.81	74,776.90	64,878.00
August	66,967.00	63,834.47	72,239.70	73,985.30
September	58,675.66	59,183.51	76,219.50	77,893.20
October	76,340.86	18,084.19	88,445.90	89,111.20
Total	600,779.26	620,102.17	752,953.35	598,318.80
Grand Total	2,572,153.58			

In 2024, total coal consumption slightly decreased to 2,572,153.58 tons, representing a reduction of approximately 24,379 tons compared to 2022. Unit 3 remained the largest consumer at 752,953.35 tons, while Unit 4 recorded the lowest consumption at 598,318.80 tons. Significant deviations occurred in April and May, when Unit 4 operated at very low levels, including no coal usage in May, indicating partial substitution with biomass. This reduction in coal use reflects the operational impact of co-firing and a decreased reliance on coal as the sole fuel source.

Table 4. Solid Biomass Consumption in 2024 (tons)

Month	Unit 1	Unit 2	Unit 3	Unit 4
January	446.562	303.131	842.046	821.046

Month	Unit 1	Unit 2	Unit 3	Unit 4
February	725.707	763.147	1,177.00	1,100.35
March	672.73	783.16	1,084.64	974.81
April	1,266.36	1,181.31	1,565.03	477.225
May	1,483.75	1,411.51	1,592.17	–
June	284.44	1,456.24	1,722.13	1,256.90
July	565.09	1,423.93	2,045.71	1,770.88
August	1,500.43	1,394.59	2,136.78	2,169.49
September	716.95	627.14	1,178.25	1,185.50
October	252.22	63.25	445.85	456.88
Total	7,914.23	9,407.40	13,789.60	10,213.08
Grand Total		41,324.31		

Solid biomass consumption in 2024 reached 41,324.31 tons, with Unit 3 recording the highest utilization at 13,789.60 tons. Peak substitution occurred in August, when all units collectively consumed more than 7,000 tons of solid biomass, indicating a higher level of reliance during that period. Compared to total coal consumption of 2,572,153.58 tons in 2024, the use of solid biomass, although still modest, contributed measurably to the generation fuel mix, accounting for an average of approximately 1.6 percent of total fuel input.

Table 5. Liquid Biomass Consumption in 2024 (kiloliters)

Month	Unit 1	Unit 2	Unit 3	Unit 4
January	50.342	244.516	16.718	–
February	108.418	126.497	–	17.562
March	87.331	178.452	77.278	39.425
April	7.295	146.231	–	12.521
May	169.281	127.821	63.897	–
June	5.6	95.964	23.673	101.092
July	183.231	122.31	78.292	52.621
August	146.469	306.15	329.32	163.366
September	212.902	173.244	64.454	10.074
October	144.437	111.517	–	–
Total	1,115.31	1,632.70	653.631	396.662
Grand Total		3,798.30		

Liquid biomass contributed an additional 3,798.30 kiloliters, with Unit 2 showing the highest consumption at 1,632.70 kiloliters. August recorded the peak usage at 945.31 kiloliters across all units, with the largest shares observed in Unit 3 at 329.32 kiloliters and Unit 2 at 306.15 kiloliters. Although the volume of liquid biomass was lower than that of solid biomass, its use reflects diversification in the co-firing strategy, with a contribution remaining below 0.2 percent of the total fuel mix. Overall fuel consumption data for Units 1–4 at the Pangkalan Susu power plant in 2024 indicate coal dominance, accounting for an average of 98.28 percent of total input. Biomass integration, consisting of 41,324.31 tons of solid biomass and 3,798.30 kiloliters of liquid biomass, contributed 1.72 percent and was successfully implemented across all units.

Table 6. Comparison of Fuel Consumption and Total CO_2 Emissions in 2024 (tons)

Unit	Coal (tons)	Coal (%)	Solid Biomass (tons)	Solid Biomass (%)	Liquid Biomass (kiloliters)	Liquid Biomass (%)
Unit 1	600,779.26	98.519	7,914.23	1.298	1,115.31	0.183

Unit	Coal (tons)	Coal (%)	Solid Biomass (tons)	Solid Biomass (%)	Liquid Biomass (kiloliters)	Liquid Biomass (%)
Unit 2	620,102.17	98.251	9,407.40	1.491	1,632.70	0.259
Unit 3	752,953.35	98.118	13,789.60	1.797	653.631	0.085
Unit 4	598,318.80	98.258	10,213.08	1.677	396.662	0.065
Total	2,572,153.58	98.276	41,324.31	1.579	3,798.30	0.145
Total CO_2 Emissions (tons)			4,053,467.12			

Unit 3 recorded the highest coal consumption as well as the largest share of solid biomass substitution at 1.80 percent, while Unit 2 showed the highest proportion of liquid biomass at 0.26 percent and Unit 4 achieved solid biomass substitution of up to 1.68 percent. These variations in substitution ratios reflect differences in technical capacity, operational strategies, and fuel supply logistics. The findings confirm that small-scale biomass integration can deliver measurable emission reductions and reinforce co-firing as a viable energy transition pathway in Indonesia. Based on the data presented in Tables 2 through 4 on coal and biomass consumption across Units 1 to 4, emissions were calculated using the IPCC 2006 methodology according to Equation 1, with the results presented in Table 7.

Table 7. Coal-Only Consumption and Total CO_2 Emissions in 2022

Month	Unit 1	Unit 2	Unit 3	Unit 4
January	102,296.70	103,966.61	103,991.04	105,037.63
February	97,992.22	102,064.20	102,321.98	47,821.08
March	112,995.58	89,320.44	123,453.39	71,313.38
April	103,120.93	79,028.73	143,767.50	124,795.87
May	115,936.23	36,570.93	143,118.89	130,113.52
June	69,192.29	112,986.63	113,621.56	118,054.18
July	114,823.57	125,333.11	111,161.92	115,743.80
August	125,076.46	120,873.26	110,740.19	136,265.11
September	103,833.46	118,190.09	59,307.10	115,028.70
October	59,435.88	55,804.07	89,441.88	77,945.95
Total	1,004,703.32	944,138.07	1,100,925.45	1,042,119.20
Total CO_2 Emissions (tons)		4,091,886.03		

Total carbon dioxide emissions from coal-only combustion in 2022 reached 4,091,886.03 tons, with Unit 3 contributing the highest share at 1,100,925.45 tons and Unit 2 the lowest at 944,138.07 tons. Monthly variations followed coal consumption trends, with higher emissions observed in May and August and relatively lower values in October. This baseline highlights the carbon-intensive nature of full reliance on coal.

Table 8. Fuel Consumption and Total CO_2 Emissions in 2024 (tons)

Month	Unit 1 (tons)	Unit 2 (tons)	Unit 3 (tons)	Unit 4 (tons)
January	118,877.18	108,396.73	121,202.46	119,941.11
February	109,605.90	111,059.88	121,704.23	118,906.84
March	99,375.93	117,021.43	122,744.17	110,700.01
April	112,500.81	100,194.92	110,909.76	36,071.66
May	111,466.40	100,519.45	111,453.37	0
June	30,917.57	110,395.70	107,387.30	75,255.25
July	45,720.02	107,269.91	117,841.22	102,241.50
August	105,533.56	100,597.00	113,842.83	116,593.73

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Month	Unit 1 (tons)	Unit 2 (tons)	Unit 3 (tons)	Unit 4 (tons)
September	92,467.21	93,267.53	120,114.62	122,752.21
October	120,305.87	28,498.95	139,382.25	140,430.70
Total	946,770.44	977,221.49	1,186,582.20	942,892.99
Total CO_2 Emissions (tons)	4,053,467.12			

In 2024, the implementation of biomass co-firing reduced total carbon dioxide emissions to 4,053,467.12 tons, representing a decrease of 38,418.91 tons compared to 2022. Among the generating units, Unit 3 recorded the highest emissions at 1,186,582.20 tons, while Unit 4 showed a significant reduction due to partial shutdown for maintenance in May, resulting in zero emissions during that period. These results confirm the role of biomass integration in lowering greenhouse gas emission intensity, even though coal remained the dominant fuel source.

Overall, the co-firing fuel mix in 2024 consisted of 98.28 percent coal, 1.58 percent solid biomass, and 0.15 percent liquid biomass. Unit 3 achieved the highest level of biomass utilization, while Unit 1 showed the greatest reliance on coal. Although substitution levels were relatively small, measurable carbon savings were still achieved, demonstrating that limited-scale biomass co-firing can meaningfully reduce emissions. These findings highlight the potential to scale up biomass co-firing as a greenhouse gas mitigation pathway aligned with carbon pricing policies and carbon credit mechanisms in Indonesia.

Discussion

Mechanisms Linking Moisture Content, Calorific Value, Combustion Efficiency, and CO_2 Emissions

Biomass moisture content plays a significant role in determining the net calorific value and combustion efficiency in co-firing systems. Biomass with high moisture content requires latent heat to evaporate water during combustion, causing part of the released energy to be used for drying rather than increasing flame temperature. As a result, the effective calorific value decreases. According to the IPCC 2006 correction, the relationship between moisture content, hydrogen content, and net calorific value is expressed as:

$$NCV = HHV - 2.442 \times (M + 9H)$$

where NCV is the net calorific value, HHV is the higher heating value, M is moisture content, and H is hydrogen content. This equation shows that increasing moisture proportionally reduces NCV. For example, palm shell biomass with a higher heating value of eighteen megajoules per kilogram and a moisture content of thirty percent experiences a noticeable reduction in net calorific value.

A lower net calorific value directly increases the amount of fuel required to achieve the same energy output, leading to higher specific fuel consumption. Boiler efficiency is also affected, as it depends on the ratio between useful steam energy and the product of fuel mass and net calorific value. Consequently, a decrease in net calorific value results in reduced boiler efficiency and increased fuel consumption. Although biomass has a lower emission factor than coal, these effects can increase carbon dioxide emission intensity per unit of electricity generated. Carbon dioxide emissions under co-firing conditions are therefore calculated following the IPCC 2006 Tier Two methodology.

Emission Analysis of Biomass Co-Firing at the Pangkalan Susu Coal-Fired Power Plant

The analysis of biomass co-firing at the Pangkalan Susu coal-fired power plant demonstrates that biomass integration contributes measurably to reducing coal consumption and greenhouse gas emissions. Under the baseline condition in 2022, when coal was used exclusively, total fuel consumption reached 2,596,532.55 tons, resulting in carbon dioxide emissions of 4,091,886.03 tons. Following the implementation of co-firing in 2024, coal consumption decreased to 2,572,153.58 tons, supplemented by

41,324.31 tons of solid biomass and 3,798.30 kiloliters of liquid biomass, bringing the total biomass share to 1.72 percent of the fuel mix. This substitution achieved an emission reduction of 38,418.91 tons of carbon dioxide, indicating that even limited biomass co-firing can deliver measurable mitigation benefits.

Differences among units indicate that co-firing performance is influenced not only by biomass substitution ratios but also by operational conditions, biomass supply, and combustion efficiency. For instance, Unit 3 recorded the highest coal consumption and emissions, while Unit 4 experienced a substantial reduction due to partial shutdown of coal operation in May 2024. Factors such as maintenance schedules, supply fluctuations, and biomass characteristics also affected emission reduction outcomes, underscoring the importance of evaluating fuel properties, particularly moisture content and calorific value, to optimize co-firing performance.

Strengthening Technical Analysis and Methodological Limitations

Although the results indicate a positive trend, the IPCC Tier Two–based analysis still has limitations because some emission factors remain default values. A Tier Three approach using unit-specific emission factors would enable more accurate estimation, particularly for emission intensity, boiler efficiency, and actual fuel consumption (Shapiro-Bengtsen et al., 2022). In addition, variability in biomass calorific value and moisture content highlights the need for sensitivity or uncertainty analysis to enhance result robustness. The current study focuses on combustion emissions, whereas upstream emissions from biomass processing and transportation also affect net emission reductions. Integrating a life-cycle assessment approach would provide a more comprehensive evaluation of the environmental impacts of co-firing (Terlouw et al., 2021).

Economic Aspects, Implementation, and Policy Relevance

From an economic perspective, the emission reduction achieved can be translated into financial value through carbon trading mechanisms, creating incentives for power plant operators to increase co-firing ratios, provided that logistical, processing, and boiler modification costs are carefully assessed (Budiarto et al., 2024; Castro-Amoedo et al., 2023). Successful implementation also requires a reliable biomass supply chain, appropriate blending systems, optimized boiler operation, and robust monitoring, reporting, and verification to ensure the credibility of carbon credits. Comparing co-firing with other mitigation strategies, such as boiler efficiency improvements and carbon capture technologies, can further clarify its role within broader decarbonization pathways in the power sector (Castro-Amoedo et al., 2023).

4. Conclusion

This study demonstrates that biomass co-firing at the Pangkalan Susu coal-fired power plant represents an effective transitional strategy for reducing greenhouse gas emissions while maintaining system reliability. The application of the IPCC methodology provides a transparent and structured framework for quantifying emissions and evaluating the impact of partial fuel substitution under real operational conditions. The findings confirm that the integration of both solid and liquid biomass can reduce fossil fuel dependence and lower carbon dioxide emissions, even when the substitution level remains relatively modest. The analysis also highlights that the effectiveness of co-firing is strongly influenced by operational factors, fuel characteristics, and supply chain conditions. Variations in moisture content and calorific value of biomass play a crucial role in combustion efficiency and emission intensity, underscoring the importance of careful fuel selection and operational optimization. Differences among generating units further indicate that technical readiness, maintenance schedules, and logistical arrangements shape emission reduction outcomes. From a broader perspective, the results emphasize that emission mitigation in the power sector does not rely solely on large-scale technological shifts. Incremental measures such as biomass co-firing can deliver measurable environmental benefits and provide practical learning pathways toward deeper decarbonization. The study also underscores the need for methodological refinement, including unit-specific emission factors and life-cycle considerations, to strengthen future assessments. Overall, this research contributes empirical evidence supporting biomass co-firing as a viable component of low-carbon energy transitions and offers relevant insights for policymakers and power plant operators seeking balanced solutions that align environmental objectives with energy security and economic considerations.

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