Evaluating the Challenges of Biomass Co-Firing for Energy Transition: A Review

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Abstract. This study explores biomass co-firing in Indonesia's coal-fired power plants as a strategic pathway to boost the country's renewable energy transition. It highlights the benefits and challenges of co-firing across three key areas: biomass supply chain mechanisms, economic feasibility, and technical obstacles. Ensuring a steady biomass supply is essential to avoid operational outages, with particular attention to challenges like slagging, fouling, and corrosion. The study reviews optimization models to determine ideal facility locations, effective co-firing rates, and strategies for emissions reduction. Economic viability is assessed using the Levelized Cost of Electricity (LCOE), which underscores the impact of biomass costs on project feasibility. The study further suggests that using additives could enhance combustion efficiency, while managing a diverse range of biomass sources, particularly in resource-rich regions, is crucial for consistent supply and the long-term sustainability of co-firing initiatives. Despite these challenges, biomass co-firing emerges as a promising option for supporting Indonesia's shift to renewable energy, with significant potential to contribute to the country's net-zero emissions target by 2060. Addressing economic, technical, and logistical factors is essential for optimizing co-firing and achieving successful, large-scale implementation.

Keywords: *Biomass; Co-Firing; Combustion; LCOE; Supply Chain*

1 Introduction

Indonesia has vast natural resources for fossil fuels and renewables, yet its power generation remains heavily reliant on coal. In 2020, coal power plants made up 48.3% of total installed capacity, gas power plants contributed 29.42%, and oil-fired plants accounted for 9.56% [1]. In 2020, all renewable energy sources, including hydro and geothermal, generated 12.72% of total electricity supply [1].

Indonesia is one of the world's largest greenhouse gas emitters, mainly due to deforestation, peatland fires, and high electricity demand. The country's reliance on fossil fuels has made it challenging to meet its Paris Agreement commitment to cut emissions by 29% by 2030, with a possible 41% reduction if international aid is provided [2]. Power generation is a major contributor to these emissions,

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especially due to the extensive use of coal-fired plants. However, Indonesia is working to lower its emissions by investing in renewable energy and implementing technologies like biomass co-firing in power plants [2].

Diversifying energy sources, including renewables, strengthens energy security by reducing dependence on fossil fuels. This helps limit risks from price fluctuations and supply interruptions, with the Indonesian Crude Price (ICP)[3] projecting a price peak of 105 USD/barrel in 2025. In Indonesia, renewable energy usage, especially biomass, remains low, with only 7 GW of total renewable resources in use and commercially available [4]. As shown in Table 1, the estimated biomass energy potential in 2021 was 32,654 MW [5]. The co-firing approach, which combines biomass and coal within a steam power plant, is considered a viable option for efficiently utilizing biomass energy [5].

Table 1 The Potential of Indonesia's Biomass [5]

Potency	**Sumatera & Kalimantan**	**Jamali**	**Sulawesi, Maluku, Papua & Nusa Tenggara**	**Total (Mwe)**
Palm Oil	12.196	60	398	12.654
Cane	399	854	42	1.295
Rubber	2.780	-	0	2.781
Coconut	63	37	78	177
Rice Husk	2.897	5353	1558	9.808
Corn	438	954	341	1.733
Cassava	117	120	33	271
Wood	1.256	14	65	1.335
Livestock Waste	112	296	127	535
City Trush	392	1527	147	2.066
Total (MWe)	20.650	9215	2791	32.654

Regarding the huge potential for biomass utilization in Indonesia, co-firing implementation remains insufficient to accelerate the energy transition. This is because many factors influence the process's execution. According to the research, several factors of production technology readiness [2], [6], [7], biomass supply continuity [2], [6], and price compatibility [2] are discussed. The optimal operation may change in the application of co-firing biomass on different technologies used in power plant generation [6] and Feed in Tarif of energy has a major role in supporting the transition energy through co-firing biomass in Indonesia [2]. Referring to the many factors that influence the application of co-firing biomass, this paper is to re-evaluate the co-firing implementation that has already been applied to the pulverized coal (PC) boiler. To obtain the best point on the aspects that affect it for PT. PLN (Persero) for reconsidering the retirement issue according to accelerating transition energy on a short-term national plan in Indonesia.

2 Co-firing Technology and Implementation

Co-firing has developed as a feasible technique for utilizing biomass, because of its technological viability, societal acceptance, and supply reliability. This strategy has been widely adopted in several developed countries, including the United States, Denmark, and the Netherlands, where biomass is co-fired in large-scale power boilers with capacities from 15 to 150 MW with a typical biomass blend ratio of 2-25% [8]. Perusahaan Listrik Negara (PLN) as Indonesia's national electricity supplier, has planned to adopt co-firing technology across its 52 coal-fired power plants (CFPPs). The biomass blending ratios in this strategy vary by boiler type, with full-scale deployment ratios of 6% for pulverized coal (PC) boilers, 40% for circulating fluidized bed (CFB) boilers, and 70% for stoker boilers [6].

There are three types of co-firing methods: direct, indirect, and parallel. The Direct Method, as shown in Figure 1(a), is the most simple and practical. It simply involves blending biomass and coal before delivering it into the boiler via the fuel nozzle. This strategy involves few changes and is frequently the most cost-effective and quick option to introduce biomass co-firing in existing facilities[6].

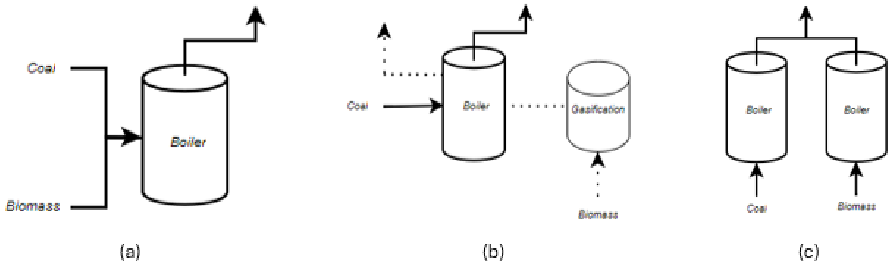

Figure 1 (a) Direct *Co-Firing*, (b) Indirect *Co-Firing,* (c) *Parallel Co-Firing* [6]

The Indirect Method, shown in Figure 1(b), involves a gasifier into the process, allowing biomass to be transformed into gas before combining with coal. While this technology supports a higher level of gasification and also offers flexibility to the operation, it requires major adjustments to the existing power plant infrastructure, raising capital expenditures due to the added gasification component if used in coal-fired power plants (CFPPs) [6].

The Parallel Method, shown in Figure 1(c), requires constructing a separate boiler for biomass combustion. Coal and Biomass are blended after the generation of steam by each boiler. However, this method requires a large amount of area and a significant investment, making it less common in Indonesia due to the high expenses [6].

As Indonesia seeks to fulfill its Nationally Determined Contribution (NDC) targets to achieve Net Zero Emissions (NZE), accelerating the transition to renewable energy is a top priority, with biomass co-firing seen as a feasible solution. The PLN's long-term power development plan (RUPTL) proposes co-firing 18 GW of CFPP capacity. This initiative could generate approximately 2.7 GW through 14 million tons of biomass per year, assuming a capacity factor (CF) of 70% [9].

However, there are some major challenges to implementing co-firing in Indonesia, particularly in terms of establishing continuous supply, preserving cost-effectiveness, and improving combustion processes. According to Madanayake et al.'s Table 2, each co-firing system Direct, Indirect, and Parallel has various benefits and constraints that must be considered during this energy transition.

Table 2 Bibliographic of advantages and disadvantages of combustion system [10]

Combustion System	Advantages	Disadvantages
Grate Furnaces (stocker)	The low investment cost for <20 MW and low operating cost [11]. Can use almost any type of wood [12]. Suitable for high moisture content biomass (10-60 wt% wb) (Cronvall, 2011; Loo and Koppejan, 2008). Suitable for fuel with high ash content and wide-scale distribution of particle size [11].	Can not be used with different combustion behaviors and ash melting points of fuel (multi-biomass) [11]. Temperature rises may cause ash melting and corrosion [13].
CFB & BFB	Fuel flexibility in calorific value, moisture content, and ash content. Fuel diversification of potential use [14]. Low Nox emission [11], [15]. A potential option to remove sulfur by injection of limestone directly [14]. Combustion efficiency is optimum even with low-grade fuel [14]. Environmental performance is good, with low emission of CO, NOx, and boiler efficiency of about 90% [15]. Relative little investment in the initiation of converting coal to biomass [12].	Needs a separate feeder in case the feeding characteristics of the co-fired fuel vary too much from the primary fuel [14]. Slagging and fouling because of high alkali content [14]. Bed agglomeration because of high alkaline and/or aluminum content [14]. Cl-corrosion on heat transfer surfaces(Superheater tubes) [15]. High investment cost. Low flexibility in particle size, high dust content in flue gas, and loss of bed material with ash [11]. Incomplete combustion and high unburned content in ash [14].
PFC	Increased efficiency due to low excess oxygen [11]. High NOx reduction is possible through using an appropriate burner [11].	Limited particle size of biomass <(10-20 mm) [11]. Low moisture content required (typically <15 wt%, wb) [14]. Decreased efficiency for high moisture fuel [14].

3 Research Review

To accomplish successful integration, the energy transition program has to consider several crucial issues, such as a strong supply chain mechanism, economic viability, and technical feasibility. This needs to be adjusted before increasing the use of co-firing biomass to accelerate Indonesia's energy transition.

3.1 Biomass Supply Chain (BSC) Mechanism

Implementing co-firing biomass and coal in existing power plants is a potential approach for reducing net carbon emissions from electricity generation. Nonetheless, the management of biomass supply raises challenges throughout the supply chain. Because biomass has lower densities in general and energy density compared to coal, a greater volume must be gathered, stored, and transported to yield an equivalent energy output. The extensive use of co-firing biomass in coal power plants depends on the development of strong supply chain systems that can supply sufficient fuel volumes securely and cost-effectively.

BSC Mechanism refers to the efficient management of available feedstock that contains potential feedstock producers, storage locations, transportation mechanisms, and power plants as consumers [16]. The complexity of biomass handling presents challenges in the modeling and optimization of biomass to bioenergy, as well as issues of availability based on feedstock seasonality, degrading quality, and raw biomass optimization logistics[17]. Feedstock seasonality concerns arise when there is insufficient variety available to back up the feedstock to generate power in line with the main plan. Degradation concerns occur during storage and treatment before transport, and logistical issues include how to reduce costs while maintaining biomass quality, quantity, and availability.

Table 3 Previous Research on Supply Chain Biomass

No	Author	Year	Method	Result
1	Mohd Idris, et al [18]	2018	MILP	Minimize overall cost and emission
2	San Juan, et al [19]	2019	MINLP	Minimize economic cost and emission
3	Aranguren, et al [20]	2021	2 Stage hub & spoke (SA metaheuristic)	Optimization for large-scale problem
4	D. Goettsch, et al [21]	2020	MILP (MLP)	Optimize depot option and final total Cost Decreased by 1,69%
5	Aranguren, et al [22]	2018	MILP	Optimization on wide condition
6	S. Ko, et al [23]	2018	MILP	Optimization in certain conditions

Based on the summary research outlined in Table 3. Refer to Figure 2 (a) for an earlier study on the biomass supply chain [18], [19], [23]. The optimization of superstructure transportation networks provides a holistic perspective of the system. A mixed-integer linear programming (MILP) model was developed to optimize the biomass supply chain, reducing overall costs and emissions by identifying ideal facility locations, optimal co-firing rates for CFPPs, and the best emission reduction strategies [18]. Sensitivity analysis showed that coal price is the most influential factor in this model [18]. The model uses the General Algebraic Modeling System (GAMS) combined with the COUENNE nonlinear solver, involving 656 continuous variables, 164 integer variables, and 425 constraints [19]. This approach efficiently balances cost and emission goals, achieving a desirability level of 0.8892 [19]. Applied to Michigan, Wisconsin, and Minnesota under current conditions with a standard woody biomass logistics system and no tax credit, the model indicates that co-firing is not viable for any plant. Even with a tax credit, increased biomass use is limited to smaller power plants unless logistics are improved [23].

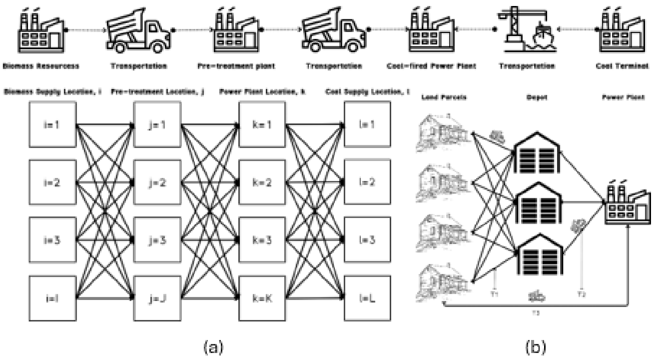

Figure 2 (a) Superstructure transportation network [18], [19], [23](b) hub and spoke model [20], [21], [22]

A mixed-integer nonlinear programming (MINLP) optimization of a superstructure transportation network was developed as a tool to assist with investment and operating decisions that minimize costs and environmental emissions while meeting energy demand and capacity restrictions [19]. Another finding showed that without considering feedstock qualities, cost, and emissions were artificially reduced, but it might cause equipment damage or loss of efficiency due to improper combustion [19].

In Figure 2 (b), the hub-and-spoke model optimizes large-scale biomass supply chains under uncertainty conditions. Using the Simulated Annealing (SA) metaheuristic, this model achieves excellent results, with a standard deviation of under 2%, and often outperforms Bender's decomposition in stochastic scenarios [20]. Another model, optimizing depot locations with MILP and a Multi-Layer Perceptron (MLP), identified 227 potential depots and reduced costs by 4.23%. After further refinement, it selected just 13 depots, achieving a 1.69% cost reduction, and demonstrating efficient depot reduction with high-quality solutions [21]. Additionally, a model using ALMANAC evaluated biomass supply across 13 scenarios, including one historical baseline and 12 future climate scenarios [22].

Optimizing biomass supply chains is crucial for co-firing success, addressing low energy density, seasonal availability, and logistics costs. Tools like MILP and hub-and-spoke models reduce costs and emissions but depend on improved logistics, coal prices, and policy support. Ensuring feedstock quality and efficient depot planning is key for sustainable implementation.

3.2 Economic Aspect

Advancing Indonesia's transition to renewable energy requires careful economic planning, considering logistics costs, biomass type and variety, technology, project scale, and location. Kebede et al.'s study on biomass co-firing in Alabama, USA, showed that co-firing can boost local economies but also raises biomass prices and competition for biomass used commercially [30]. Key costs include raw materials and transport, while pellet mills producing over 10 tons per hour can reduce capital expenses. Additionally, the varied properties of biomass lead to higher maintenance costs [30]. Smith et al. found that raw biomass costs, making up 40-80% of energy depot expenses and 65-95% at power plants, are critical to co-firing feasibility [31].

Table 4 Study literature result for the economical aspect in the implementation of Co-Firing.

No	Location	Cases	Result
1	China (Yunnan and Shandong Province)	Energy transition through co-firing biomass	LCOE is around US$ 3.55 – 14.46 /MWh [32].
2	Alberta, Western Canada	Comparison between average electricity pool price with LCOE for co-firing coal with wood chips, straws, and forest residue	The LCOE value for co-firing with: Wood chips $56.42/MWh Straws $57.35/MWh Forest residues $54.50/MWh All results at a 95% confidence level [33].
3	North Central US	Comparison result between the storage mechanism of biomass handling	The LCOE result value of torrefied pelletized biomass Scenario 1, $48.6/MWh Scenario 2, $76/MWh where Scenario 1 torrefied pelletized biomass was stored separately and in Scenario 2 with the directly mixed mechanism [31].
4	China	Comparison between CFR percentage on	The LCOE results for 3 scenarios are shown: PC Plant, $48,4/MWh PBC Plant, $53.86 - 67.48 /MWh

No	Location	Cases	Result
		transition coal with biomass	PB Plant, $95.2/MWh These 3 scenarios are being studied through variations of CFR in China [34].

Table 4 shows that capacity factor ratio (CFR) percentage on different biomass as fuel supply affects the financial aspect output, the inclination of CFR on co-firing percentage growth linear with LCOE cost from each case. As shown in Figure 3, the national average cost-benefit values are $2.61/MWh for a 10% blending ratio and respectively raise to $30,42/MWh at a 100% blending ratio. This result shows that the cost or benefit of biomass co-firing that represents LCOE raises linearly with the blending ratio percentage [32]. The power plant located in Yunnan province with a capacity of 4 MW has shown the greatest economic cost than the power plant located in Shandong province with a capacity of 350 MW which shows the least economic cost [32].

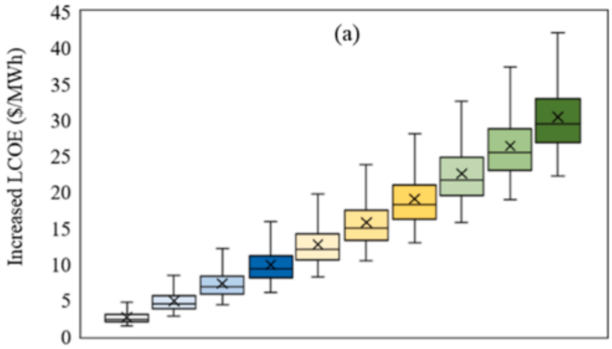

Figure 3 Box plot of incremental LCOE in China [32]

Smith et al. developed a simulation tool for decision-making to evaluate biomass co-firing in existing power plants. In scenario 1, pelletized torrefied biomass is stored separately, while in scenario 2, it is blended directly with coal, avoiding additional facilities. A simplified LCOE analysis shows that scenario 1 has a lower LCOE at $48.6/MWh, compared to $76/MWh in scenario 2 [31]. According to Bo Yang et al., an increase in the CFR raises the LCOE. For example, the LCOE for a pulverized coal (PC) plant without incentives is $48.4/MWh, which rises to $53.86-$67.48/MWh for a plant using pulverized biomass-coal (PBC), and up to $95.2/MWh for a pure biomass (PB) plant [34], As an example, Co-firing 15% biomass increases the LCOE by 10.7%, and 20% biomass raises it by 19.1% [29]. Additionally, the LCOE is sensitive to the amount of biomass used, interest rates, and biomass prices, making it responsive to economic shifts.

Biomass co-firing increases LCOE as blending ratios grow, influenced by biomass type, storage methods, and capacity factor. Larger plants achieve lower costs due to economies of scale, while interest rates and biomass prices significantly impact feasibility. Efficient logistics and targeted incentives are critical to optimizing economic viability and reducing costs.

3.3 Technical Aspect

Implementing co-firing in Indonesian power plants presents a promising approach to reducing greenhouse gas emissions while utilizing widespread domestic resources, but some technical challenges must be overcome such as slagging, fouling, abrasion, corrosion, and biomass retention time. Ash-related issues arise when co-firing coal with different types of biomasses, especially in PC boilers. Hariana et al. observed this when using various biomasses, including EFFR, RH, SRF, and WC. As shown in Table 5, each biomass had a lower maximum temperature (T_{max}) than coal, indicating higher reactivity. Among the materials, wood chips experienced the greatest weight loss during combustion, while EFFR had the shortest burn time and the smallest temperature difference between T_{bo} and T_{ig}, at around 81.88°C[30].

Table 5 TGA-DTA analysis results for coal and biomass blends [30]

Sample	T_{ig} (ºC)	T_{bo} (ºC)	T_{max} (ºC)	T_{bo} - T_{ig} (ºC)	R_{max} (mg/s)
Coal	295.00	558.52	397.88	263.52	0.04
EFFR	248.59	330.47	307.47	81.88	0.15
RH	257.82	485.49	312.07	227.67	0.02
SRF	254.62	535.55	453.57	280.93	0.04
WC	259.99	375.64	318.75	115.65	0.20
25% EFFR	276.19	560.06	396.42	283.87	0.03
25% RH	276.07	551.42	401.09	275.35	0.04
25% SRF	264.88	545.57	418.19	280.69	0.04
25% WC	272.03	552.66	407.40	280.63	0.05

To improve co-firing combustion, additives can be used to reduce slagging, fouling, and corrosion. Table 6 shows the effectiveness of various additives MgO, Al2O3, CaHPO4, and SiO2 at 1%, 3%, and 6% proportions in a 15% biomass and coal mixture with EFFR. Notably, adding MgO increases the ignition temperature as its proportion rises [37].

Table 6 TGA-DTA analysis results for coal and EFFR blends with addition 1, 3, and 6% wt MgO, Al_2O_3, $CaHPO_4$, and SiO_2 [31]

Sample	T_{ig} (ºC)	T_{bo} (ºC)	T_{max} (ºC)	T_{bo} - T_{ig} (ºC)	R_{max} (mg/s)
Coal	285.80	459.67	430.50	173.87	0.04
EFFR	248.59	330.47	248.59	81.88	0.15
C15	266,74	511.04	430.73	244.30	0.04
C15-R1	268.77	503.39	431.09	234.62	0.04
C15-R3	272.83	518.93	418.98	246.10	0.03
C15-R6	268.92	523.22	419.81	254.30	0.03
C15-H1	275.13	474.00	428.79	198.87	0.04

Sample	T_{ig} (°C)	T_{bo} (°C)	T_{max} (°C)	T_{bo} - T_{ig} (°C)	R_{max} (mg/s)
C15-H3	358.79	484.08	428.31	125.29	0.04
C15-H6	267.44	550.55	424.00	283.11	0.03
C15-I1	267.03	516.13	422.58	249.10	0.03
C15-I3	287.30	511.81	429.18	224.51	0.04
C15-I6	259.74	541.00	410.07	281.26	0.04
C15-T1	284.46	503.42	420.85	218.96	0.03
C15-T3	276.86	510.55	420.07	233.69	0.04
C15-T6	276.83	514.02	428.91	237.19	0.04

Incomplete combustion marked by insufficient burn-out temperatures can lead to unburned ash which contributes to slagging and fouling. Ignition temperature influences ash behavior during combustion and lower ignition temperatures may cause ash to aggregate and deposit early, while maximum combustion temperatures affect ash properties. Table 7 shows the predicted tendencies for slagging, fouling, abrasion, and corrosion for different fuels, biomass EFFR and SRF show the highest slagging potential, coal the highest fouling potential, RH the highest abrasion score, and SRF the highest corrosion score. This data indicates that using SRF for power generation should be limited to reduce downtime risks because of the corrosion score [30].

Table 7 Prediction slagging, fouling, abrasion, and corrosion tendencies for single fuel system [30]

Parameter	Max	Coal	EFFR	RH	SRF	WC
Slagging Score	7.0	3.0	5.5	2.0	5.5	3.5
Fouling Score	3.0	3.0	2.0	0.5	1.5	2.0
Abrasion Score	1.0	0.0	0.0	1.0	1.0	0.0
Corrosion Score	2.0	0.0	1.0	1.0	2.0	0.5

Table 8 shows that in a co-firing system with a 25% biomass blend, there is a notable reduction in slagging, fouling, abrasion, and corrosion tendencies. Specifically, the slagging score decreases by about 2 points when using coal in co-firing, while the corrosion score drops by roughly 0.5 points when co-firing with wood chips [36].

Table **8** Prediction, Slagging, fouling, abrasion, and corrosion tendencies for 25% biomass blend [30]

Parameter	Max	25% EFFR	25% RH	25% SRF	25% WC
Slagging Score	7.0	3.5	2.5	5.5	3.5
Fouling Score	3.0	3.0	1.5	2.0	2.0
Abrasion Score	1.0	0.0	0.5	0.5	0.0
Corrosion Score	2.0	0.0	0.0	0.5	0.0

When the co-firing ratio increased from 0% to 30%, ash accumulation became an issue, especially impacting aluminum (Al) and silicon (Si) content during both untagged and air-staged combustion. Alkali metals in the ash increased slag viscosity, binding ash particles together. To reduce ash buildup, air-staged combustion is recommended, particularly at co-firing ratios of 20% or higher [38]. Table 9 shows that using PSA as the main fuel instead of coal produces the highest fouling and slagging indexes. At 600°C and 800°C, these indexes increase, but the slag viscosity index decreases significantly with higher PSA content [39].

Table 9 Fouling and slagging indices for different ashes [33]

Temperature	Sample	Slagging index	Fouling index	Slag Viscosity index
600°C	JCA	0.16 (low)	0.441 (low)	83.27 (low)
	PSA	3.64 (severe)	51.60 (extremely high)	21.92(high)
	JC70PS30	0.45 (low)	3.36 (high)	67.89 (medium)
	JC50PS50	0.78 (medium)	10.50 (high)	57.89 (high)
	JC30PS70	1.59 (high)	24.97 (high)	38.31 (high)
815°C	JCA	0.16 (low)	0.34 (low)	82.09 (low)
	PSA	1.80 (severe)	22.69 (high)	35.11 (high)
	JC70PS30	0.50 (low)	2.21 (high)	61.53 (high)
	JC50PS50	0.75 (medium)	6.38 (high)	53.28 (high)
	JC30PS70	1.30 (high)	15.08 (high)	41.92 (high)

The characteristics of ash produced in power plant combustion are affected by variables such as biomass type, blending ratio, material handling, and mineral interactions [41]. These variables need to be managed carefully regarding the issue of alkali content.

Co-firing in Indonesian power plants will face challenges like slagging, fouling, and corrosion. Additives like MgO improve efficiency, while air-staged combustion reduces ash issues at higher co-firing ratios. Biomass type and ratio significantly affect maintenance and reliability.

4 Conclusion

Co-firing biomass in coal-fired power plants represents an effective approach to decrease carbon emissions and utilize renewable energy resources. This approach encounters considerable challenges, such as feedstock seasonality, quality degradation, and elevated logistical costs. Advanced optimization techniques, including Simulated Annealing (SA) and Mixed-Integer Linear Programming (MILP), effectively minimize costs and emissions through the optimization of facility placement, transportation, and co-firing rates. Future research must incorporate feedstock quality, cost, and emissions into comprehensive supply chain models, while also examining emerging innovations like machine learning-optimized decentralized depots. Pilot projects and computational advancements are essential for ensuring the scalability of these solutions across various biomass types and regional contexts.

The economic feasibility of biomass utilization in Indonesia is constrained by higher transportation costs and raw material expenses. Smaller plants frequently exhibit greater cost-effectiveness, highlighting the necessity for measures aimed at scale efficiency. Financially sustainable solutions necessitate the adoption of decentralized pelletizing technologies, direct coal-biomass blending, and customized regulatory frameworks. Future research should concentrate on creating decision-support models and Levelized Cost of Energy (LCOE) analyses developed to the specific conditions and regional biomass potential of Indonesia. Pilot projects will be essential for validating these strategies and ensuring alignment with Indonesia's renewable energy targets.

Co-firing biomass presents technical challenges, including slagging, fouling, corrosion, and ash-related issues, which are influenced by reduced combustion temperatures and increased biomass reactivity. Specific feedstocks, including SRF and EFFR, present considerable risks, especially at elevated blending ratios, owing to heightened slagging and corrosion potential. Mitigation strategies, such as the incorporation of MgO and CaHPO4 additives alongside air-staged combustion techniques, demonstrate the potential to enhance system reliability. Future research should prioritize cost-effective additives, advanced modeling of ash behavior, and the refinement of air-staging methods to facilitate higher biomass co-firing ratios, thereby ensuring efficiency and long-term operational stability.

Addressing supply chain, economic, and technological challenges while expanding biomass sources and improving availability can make biomass co-firing a key solution for reducing emissions and supporting sustainable energy transitions.

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