

Development of a biomass supply chain ecosystem to support co-firing in Indonesian CFPPs for energy transition success

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Abstract. Biomass, as a renewable energy resource, plays a strategic role in Indonesia's energy transition, particularly in achieving the Enhanced Nationally Determined Contribution (ENDC) 2030 and the Net Zero Emissions (NZE) 2060 targets. One of the key strategies is the co-firing program in coal-fired power plants (CFPPs), which allows partial substitution of coal with biomass without requiring large investment costs or long implementation times. However, the success of this program depends on the establishment of a biomass supply chain ecosystem, a collaborative, multi-actor network involving suppliers, processors, end-users, regulators, and supporting institutions that interact with each other to create sustainable value. Unlike traditional linear supply chains, this ecosystem requires interdependence, co-creation, and value-based coordination among heterogeneous actors. In the Indonesian context, this approach is critical to address the complexities of governance, logistics, and sustainability while aligning cross-sectoral interests. Current regulatory frameworks remain insufficient compared to more established energy sectors, leading to gaps in coordination, pricing mechanisms, and long-term supply security. Developing a biomass supply chain ecosystem supported by effective regulatory policies could generate significant multiplier effects, particularly for smallholders and micro-enterprises, and is essential for the success of Indonesia's energy transition.

1 Introduction

1.1 Background

The global push for decarbonization has made energy transition an imperative for both developed and developing countries. Indonesia, as the largest coal consumer in Southeast Asia, relies heavily on coal-fired power plants (CFPPs), which account for more than 60% of the national electricity mix and are the largest contributors to greenhouse gas (GHG) emissions in the power sector [1]. To align with international commitments, Indonesia has pledged to reduce emissions by 41% by 2030 under the Enhanced Nationally Determined Contribution (ENDC) and to achieve Net Zero Emissions (NZE) by 2060.

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One pragmatic strategy adopted to accelerate this transition is biomass co-firing, which involves substituting a portion of coal with biomass in existing CFPPs. This approach offers significant advantages: it requires minimal capital investment, can be deployed rapidly without constructing new plants, and immediately reduces emissions [2]; [3]. PT Perusahaan Listrik Negara (PLN, Persero), the Indonesian state-owned electricity company has initiated co-firing projects in 52 locations of CFPPs and targets the use of 9–10 million tons of biomass annually by 2030, equivalent to a reduction of over 11 million tons of CO_{2e} per year [4]; [5].

However, the successful scaling of biomass co-firing is not merely a technological challenge. It also depends on addressing systemic barriers such as fragmented supply chains, logistical inefficiencies, economic constraints, and regulatory gaps

1.1 Research Problem & Gap

While the technical feasibility of biomass co-firing is well established in both domestic and international contexts [6]; [7], the primary barrier in Indonesia lies in the lack of a robust supply chain ecosystem. Current supply arrangements are fragmented:

- 1) Upstream: farmers, cooperatives, and Micro, Small, and Medium Enterprises (MSMEs) face unstable prices, limited access to finance, and weak organizational capacity.
- 2) Midstream: processors and logistic providers contend with inconsistent feedstock and inadequate infrastructure.
- 3) Downstream: PLN and CFPPs face price uncertainty, as biomass pricing is still pegged to coal under the Domestic Market Obligation (DMO) regime.
- 4) Regulators: multiple ministries (Energy, Agriculture, Environment, Forestry, Finance) operate with overlapping mandates, resulting in fragmented governance and limited policy coherence.

Existing studies on co-firing have focused on technical aspects and emission reductions but have rarely integrated multi-actor perspectives into policy analysis. Consequently, there is a knowledge gap in understanding how to design and govern a sustainable biomass supply chain ecosystem in a developing country context like Indonesia.

Existing studies on co-firing primarily focus on technical aspects and emission reductions. However, only a few integrate multi-actor perspectives with policy analysis

1.1 Objectives

This paper aims to develop a comprehensive framework for the biomass supply chain ecosystem to support co-firing in Indonesian CFPPs, bridging the technical, policy, and governance dimensions. Specifically, the objectives are to:

1. Map the multi-actor ecosystem involved in the biomass supply chain, including their roles, interests, and interdependencies.
2. Evaluate policy and regulatory frameworks, both national and international, to identify gaps and opportunities for improvement.
3. Propose actionable policy recommendations supported by multi-actor to ensure long-term supply reliability, economic viability, and sustainability.

By addressing these objectives, the study contributes to the academic discourse on sustainable supply chain ecosystems while offering practical policy insights for Indonesia's energy transition.

2 Literature Review

2.1 Biomass and co-firing in global energy transition

Globally, biomass is considered a carbon-neutral renewable energy source, as the carbon released during combustion is offset by the carbon absorbed during the plant's growth cycle [3]. Co-firing biomass in existing coal-fired power plants has been implemented in several countries, including the United States, the United Kingdom, Japan, South Korea, and across the European Union. These countries view co-firing as a low-cost, transitional strategy to reduce emissions while renewable capacity such as solar and wind is expanded [8]; [9].

International experiences highlight that co-firing is not only technically feasible but also economically viable when supported by subsidies, feed-in tariffs, or carbon pricing mechanisms. For example, the United Kingdom has successfully co-fired at the Drax Power Station, enabled by strong regulatory frameworks and financial incentives. Similarly, Japan and South Korea rely on co-firing to diversify their energy mix, reduce dependency on imported coal, and stimulate domestic biomass industries [7].

2.2 Current status of biomass co-firing in Indonesia

In Indonesia, biomass co-firing has moved beyond pilot projects into broader implementation. By 2025, 48 CFPPs were already operating with biomass co-firing, and PLN aims to expand this to 52 plants by 2030. The scale of this program requires an estimated 9–10 million tons of biomass annually, sourced primarily from agricultural residues, forestry by-products, and dedicated energy crops [4].

This progress highlights Indonesia's commitment to embedding biomass within the national energy mix. Nevertheless, several structural challenges remain. The supply of biomass is often inconsistent, depending heavily on smallholders, cooperatives, and micro-enterprises with limited access to capital and unstable market conditions. Logistics are constrained by inadequate storage, processing, and transportation infrastructure, which increases costs, particularly for plants located outside Java. In addition, the pricing of biomass remains pegged to coal benchmarks, reducing incentives for producers and investors [5]. These issues underscore the importance of shifting from fragmented supply arrangements toward an integrated ecosystem approach.

2.3 Supply Chain vs. Ecosystem Approaches

Traditional supply chains are typically linear, linking suppliers and buyers through transactional relationships. This model often fails when dealing with complex systems that involve diverse actors and sustainability objectives. By contrast, a supply chain ecosystem is characterized by interdependence, co-creation, and value-based coordination among heterogeneous stakeholders [10].

In the biomass sector, the ecosystem model implies the integration of upstream producers (farmers, cooperatives, MSMEs), midstream actors (processors, logistic providers, BUMD/BUMN), and downstream users (PLN and industrial consumers), supported by regulators, financial institutions, and civil society organizations. Such a framework can strengthen supply stability, reduce transaction costs, and generate shared economic and social value [11]. For Indonesia, where production is geographically dispersed and actor capacities are highly uneven, the ecosystem approach offers a way to manage complexity while pursuing sustainability

2.4 Regulatory and policy frameworks

Regulation plays a central role in enabling or constraining biomass utilization. In advanced economies, governments have established comprehensive policy tools such as renewable portfolio standards, feed-in tariffs, carbon markets, and targeted subsidies, creating stable investment climates and encouraging innovation [12].

Indonesia has introduced several important policies, including:

- Ministerial Regulation ESDM No. 12/2023, mandating dispatch priority for co-firing plants;
- Ministerial Decree No. 255.K/30/MEM/2020, providing technical guidelines for biomass co-firing;
- Early carbon pricing initiatives under the *Persetujuan Teknis Batas Ambang Emisi* (PTBAE) for CFPPs.

Yet, implementation challenges persist. The biomass pricing system remains linked to coal benchmarks through the Domestic Market Obligation (DMO), undermining the competitiveness of biomass for suppliers. Moreover, overlapping mandates across ministries Energy, Agriculture, Environment and Forestry, Finance, result in fragmented governance and regulatory uncertainty [4]. Strengthening regulatory coherence and introducing tailored economic incentives will be critical for scaling up biomass co-firing.

2.5 Research Gap

The reviewed literature shows that while the technical feasibility of biomass co-firing and its contribution to reducing emissions are well documented, there are still important gaps in the Indonesian context. First, most studies emphasize technological and engineering aspects, with limited attention to the governance and policy frameworks required to sustain large-scale implementation. Second, the multi-actor nature of the biomass supply chain is often overlooked. Farmers, cooperatives, MSMEs, local governments, PLN as the off-taker, regulators, and financial institutions all have distinct roles, interests, and constraints that must be aligned to ensure ecosystem resilience.

Third, research exploring the regulatory environment for biomass in Indonesia remains scarce. Unlike established energy sources, biomass lacks a comprehensive pricing mechanism, clear investment incentives, and an integrated coordination platform across ministries. This creates uncertainty for investors and weakens the participation of local communities and small-scale enterprises.

Finally, there is a shortage of empirical studies examining how biomass supply chains can be transformed into ecosystems that generate shared value not only for emission reduction but also for rural development, job creation, and community empowerment.

This study addresses these gaps by proposing a framework that integrates multi-actor perspectives and regulatory analysis to design a sustainable biomass supply chain ecosystem tailored for Indonesia's energy transition.

3 Methodology

3.1 Research Design

This study adopts a qualitative, policy-oriented research design that combines literature review, stakeholder mapping, and policy analysis. The approach emphasizes understanding the interplay between multiple actors, their interests, and regulatory frameworks in shaping

the biomass supply chain ecosystem for co-firing in Indonesia. The study draws upon secondary data from official policy documents, PLN reports, and regulatory publications, complemented by stakeholder mapping outcomes from previous focus group discussions (FGDs) and workshops conducted with PLN, MEMR, and biomass suppliers. These sources provide the empirical basis for the multi-actor policy analysis (MAPA) and the comparative case studies of Indramayu, Jeranjang, and Air Anyir CFPPs.

3.2 Multi-Actor Policy Analysis (MAPA)

To capture the complexity of stakeholder interactions, the study applies Multi-Actor Policy Analysis (MAPA). MAPA identifies key actors in the biomass supply chain, analyzes their perceptions, goals, interests, and resources, and evaluates how these influence policy outcomes. The actor categories include:

- Upstream producers: farmers, cooperatives, village enterprises (*Bumdes*), and micro, small, and medium enterprises (MSMEs).
- Midstream actors: biomass processors, logistics companies, regional-owned enterprises (*BUMD*), and state-owned enterprises (*BUMN*).
- Downstream users: PLN as the main off-taker and industrial consumers.
- Regulators and support institutions: ministries (Energy, Agriculture, Environment and Forestry, Finance), local governments, investment authorities, financial institutions, and trade associations.

This mapping is based on a structured table of actors, which details their perceived problems, objectives, interests, constraints, and policy implications

3.3 Case Studies

The analysis focuses on three case-study locations in Indonesia where biomass co-firing has been implemented:

1. Indramayu CFPP (West Java) – represents co-firing in a densely populated region with significant agricultural residues.
2. Jeranjang CFPP (West Nusa Tenggara) – reflects co-firing challenges in an island system with potential waste logistics but limited infrastructure.
3. Air Anyir CFPP (Bangka) – highlights co-firing potential from forestry and plantation residues.

These cases were selected to illustrate diverse geographic, logistical, and socio-economic conditions that affect biomass supply chain development.

3.4 Data Sources

The study uses a combination of primary and secondary data. Secondary data were collected from government regulations, PLN reports, academic publications, and international benchmarks. Primary insights were derived from stakeholder consultations, workshops, and policy briefs on biomass co-firing. Actor mapping data were enriched using the multi-actor table, which provides structured insights into roles, resources, and policy positions.

3.5 Analytical Framework

The analytical framework integrates:

1. Stakeholder mapping to identify power, interests, and resources of key actors.
2. Policy analysis to assess the adequacy of existing regulations and identify gaps.
3. Comparative benchmarking against international experiences in biomass co-firing (including Europe, Japan, South Korea).

The combination of these methods enables the study to capture both the institutional and the policy requirements for building a resilient biomass supply chain ecosystem in Indonesia.

4 Results

4.1 Biomass potential and demand in Indonesia

The field assessment and case studies confirmed that while Indonesia's technical biomass potential exceeds **500 million tons per year**, the volume that can be realistically mobilized for co-firing is far smaller due to collection, logistics, and market barriers.

- In **Indramayu CFPP (West Java)**, abundant rice husks and wood waste residues were identified, but only 35–40% of the residues can be secured consistently because of competing uses (animal feed, fertilizer, industrial offtaker).
- In **Jeranjang CFPP (West Nusa Tenggara)**, biomass resources exist, but supply is dominated by MSMEs with limited financial and technological capacity. Despite constraints, the sector is growing rapidly, indicating potential if adequate support is provided
- In **Air Anyir CFPP (Bangka)**, forestry residues and rubber wood waste show higher potential, with preliminary estimates of 150,000–200,000 tons annually, but variability in moisture content and lack of preprocessing facilities reduce effective utilization.

Overall, current mobilization capacity is around 3–4 million tons per year, compared to PLN's target of 9–10 million tons by 2030, leaving a shortfall of 5–6 million tons that must be addressed through increased investment and stronger coordination.

4.2 Actor mapping and interdependencies

The multi-actor analysis highlights that the biomass supply chain involves diverse stakeholders with different interests, yet they are highly interdependent. The simplified mapping below summarizes the key actors:

Table 1. Summary of key actors in the biomass supply chain ecosystem

Actor	Key Issues	Interests	Constraints	Policy Implications
Farmers	Low profit from biomass crops	Fair prices, income stability	Price fluctuation, market access	Subsidy or price stabilization mechanisms
Cooperatives / MSMEs	Weak bargaining power, limited	Market access, business growth	Lack of finance & technology	Training, access to credit, cluster

	capacity			development
PLN (Off-taker)	Needs reliable, low-cost supply	Secure long-term biomass contracts	Bound to coal-linked DMO pricing	Establish fair biomass pricing scheme
Regulators (Ministry)	Fragmented policy mandates	Promote energy transition & sustainability	Overlapping regulations, weak coordination	Integrated policy and stronger inter-ministerial body
Logistics Providers	High transport & handling costs	Efficient supply chain operations	Poor infrastructure, scattered feedstock	Investment in infrastructure & logistics hubs

This mapping shows that no single actor can succeed in isolation. Farmers and MSMEs depend on fair pricing and support, PLN requires reliable contracts, regulators need better coordination, and logistics providers require infrastructure upgrades. Building an ecosystem approach is therefore essential to align these diverse interests.

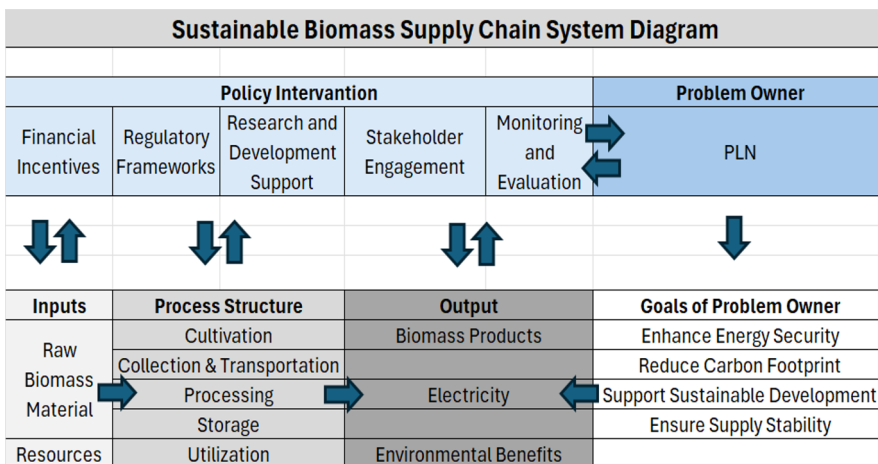


Fig. 1. Sustainable Biomass Supply Chain System Diagram

4.3 Supply Chain and Policy Gaps

The case studies reveal that although biomass resources are available, the supply chain remains fragmented and inefficient. At the upstream level, farmers and MSMEs provide most of the feedstock, but their limited capacity results in inconsistent volumes and quality. Midstream actors, particularly cooperatives and local enterprises, lack sufficient infrastructure for preprocessing and storage. Logistic providers highlight that the absence of dedicated hubs and reliable transport routes increases delivery costs, particularly for plants outside Java.

From the policy perspective, the analysis shows that biomass is not yet supported by a robust regulatory framework. While regulations exist, pricing is still pegged to coal under the Domestic Market Obligation (DMO), which discourages long-term investment. The absence of biomass quality standards and certification systems further complicates integration into CFPPs operations. These findings indicate that the main barrier is not resource availability,

but the absence of an ecosystem-level coordination mechanism that ensures continuity and reliability from upstream to downstream.

4.4 Economic and Regulatory Barriers

Economic assessment confirms that the **delivered cost of biomass** in many locations remains above the benchmark price of coal. In Indramayu, competition for rice husks reduces availability for energy use. In Jeranjang, although MSMEs are rapidly expanding, their limited financial capacity prevents scaling to meet PLN's demand. In Air Anyir, the absence of preprocessing technologies leads to inefficiencies such as high moisture content, reducing boiler performance.

Regulatory barriers are closely related. The **overlap of mandates** between MEMR, Agriculture, and Environment ministries creates delays in program implementation. PLN, as the off-taker, cannot offer long-term contracts due to the lack of a nationally recognized **biomass pricing mechanism**. Without such a mechanism, suppliers remain exposed to market volatility, while financial institutions remain reluctant to provide credit due to perceived risks.

These results show that achieving the 2030 target of 9–10 million tons annually requires not only mobilizing feedstock but also **creating a conducive regulatory and economic environment** that secures investment and aligns incentives across actors.

Summary of Results

- Biomass resources are technically abundant but practically constrained, with only 20–30% of potential being mobilized under current conditions (4.1).
- The supply chain involves multiple interdependent actors, where the weaknesses of one actor (e.g., farmers, MSMEs, logistics) directly affect the system as a whole (4.2).
- The main gaps are not in feedstock availability but in coordination, infrastructure, and policy alignment (4.3).
- Without reforms in pricing, regulation, and investment frameworks, biomass will remain more expensive and less attractive than coal, slowing down the transition (4.4).

These findings underline the urgency of developing a biomass supply chain ecosystem that integrates actors, aligns policies, and creates fair economic incentives to enable co-firing at scale.

5 Discussion

5.1 Strategic Role of Biomass Supply Chain Ecosystems

The results indicate that Indonesia's biomass resources are abundant but underutilized, with only 20–30% of the technical potential mobilized under current conditions. This mismatch between potential and realizable supply highlights that the core challenge is institutional and systemic, rather than biophysical. By moving from fragmented supply chains toward a biomass supply chain ecosystem, Indonesia can integrate farmers, MSMEs, processors, logistics providers, regulators, and financial institutions into a coordinated network that secures feedstock reliability, reduces transaction costs, and ensures long-term sustainability.

5.2 International Benchmarking

International experiences reinforce this conclusion. In the United Kingdom, strong policy incentives such as subsidies and renewable portfolio standards enabled Drax Power Station to transition part of its fuel to biomass. Japan and South Korea have also expanded co-firing by providing clear feed-in tariffs and co-firing quotas, creating a predictable market environment for investors. These cases illustrate that policy certainty, pricing mechanisms, and support for local producers are decisive factors for scaling biomass use.

Compared with these countries, Indonesia lacks a comparable level of regulatory support. Biomass pricing remains linked to coal benchmarks through the Domestic Market Obligation (DMO), and there is no standardized certification system for biomass quality. This gap explains why, despite resource abundance, supply mobilization remains below target.

Table 2. International benchmarking of biomass co-firing policies [7]

Country	Policy Instruments	Future Outlook
European Union	Energy Roadmap 2050	Co-firing as part of long-term transition strategy
United Kingdom	Renewable Obligation, ROCs, Energy Crop Scheme	Moving toward dedicated biomass plants
Netherlands	MEP, SDE, Dutch Energy Accord	Limited by high costs and subsidy reduction
Germany	Renewable Energy Sources Act, Feed-in Act	Biomass availability challenges, no specific incentives
Denmark	PSO, Renewable Energy Act	Strong policy support but reliant on costly imports
United States	Renewable Portfolio Standards (RPS)	Focus shifting to biofuels; dependent on state-level incentives
Canada	Provincial initiatives (Ontario dominant)	Opportunities in other provinces after Ontario phase-out
Japan	RPS, FiT	Potential significant role, but biomass supply unstable
South Korea	Renewable energy quota including biomass	Increasing role in energy strategy with stronger support
Brazil	Pro-Alcool (ethanol program)	Early stage but promising due to abundant agricultural residues

5.3 Policy Implications for Indonesia

The findings suggest several key policy implications:

1. Establish a dedicated biomass pricing mechanism, such as an *Indonesian Biomass Index (IBI)*—that reflects production costs, sustainability standards, and carbon benefits, independent from coal prices.

2. Strengthen institutional coordination by creating an inter-ministerial body that unites the Ministry of Energy and Mineral Resources (MEMR), the Ministry of Agriculture, and the Ministry of Environment and Ministry of Forestry under a single biomass strategy.
3. Support upstream producers through targeted subsidies, training, and access to credit for farmers, cooperatives, and MSMEs.
4. Invest in infrastructure and logistics, particularly preprocessing facilities and transport hubs, to reduce high delivery costs in regions outside Java.
5. Introduce standardization and certification systems for biomass quality to reduce uncertainty for CFPP operators.
6. Incentivize private sector participation through carbon pricing, green financing, and risk-sharing instruments to attract investment into biomass cultivation and processing.
7. Implement Domestic Market Obligation (DMO) for strategic biomass commodities, such as palm kernel shell (PKS), to secure stable domestic supply for co-firing while balancing export interests.

Table 3. Policy options for strengthening Indonesia's biomass co-firing ecosystem

Issue	Policy Option	Expected Impact
Price uncertainty	Establish Indonesian Biomass Index (IBI) independent from coal prices	Fair pricing, market stability, investment confidence
Fragmented governance	Create inter-ministerial coordination body (MEMR, Agriculture, Environment & Forestry)	Unified strategy, reduced policy overlap, stronger enforcement
Weak upstream capacity	Provide subsidies, training, and credit access for farmers, cooperatives, MSMEs	Stronger supply base, empowerment of rural economy
High logistics costs	Invest in preprocessing facilities and transport hubs, especially outside Java	Lower delivery costs, improved supply chain reliability
Quality inconsistency	Develop standardization and certification systems for biomass feedstock	Reduced risk for CFPPs, quality assurance
Limited private investment	Incentivize participation via carbon pricing, green financing, risk-sharing instruments	Attract domestic and foreign capital, stimulate innovation
Export-driven feedstock (PKS)	Implement Domestic Market Obligation (DMO) for strategic commodities like PKS	Secured domestic biomass supply, balanced export and energy security

5.4 Toward a Multi-Actor Collaboration Model

The actor mapping confirms that no stakeholder can succeed in isolation. Farmers need fair prices, MSMEs require capital and technology, PLN depends on secure supply, and regulators need stronger coordination. An ecosystem-based collaboration model is therefore essential. Such a model would position PLN as the anchor off-taker, supported by cooperatives and MSMEs as aggregators, with MEMR, Ministry of Environment and Ministry of Forestry providing regulatory oversight, and financial institutions de-risking investment through green credit schemes.

This aligns with the broader principle of value co-creation in supply chain ecosystems, where diverse actors share both risks and benefits. By adopting this model, Indonesia can not only achieve its co-firing targets but also generate socio-economic co-benefits, including rural job creation, income diversification for farmers, and empowerment of local enterprises.

This paper contributes by framing biomass supply not merely as a chain of transactions, but as an ecosystem that stitches actors together through interdependence, coordination, and shared value creation.

6 Conclusion

This study shows that the greatest challenge for Indonesia's biomass co-firing program is not the lack of resources, but the absence of a system that can stitch together the diverse actors into a coherent whole. Farmers, cooperatives, MSMEs, PLN, regulators, and logistic providers each play critical roles, yet their interdependence means that weaknesses at one point ripple across the entire chain.

The concept of a biomass supply chain ecosystem offers a way forward. Unlike a linear chain, the ecosystem approach recognizes the need for collaboration, coordination, and shared value creation among all stakeholders. By weaving together the interests of upstream producers, midstream processors, downstream off-takers, and regulators, the ecosystem becomes the fabric that transforms fragmented efforts into a resilient and sustainable system.

International experiences demonstrate that when such ecosystems are supported by clear policies, fair pricing mechanisms, and investment incentives, biomass can evolve from a marginal fuel into a strategic pillar of energy transition. For Indonesia, building this ecosystem is essential not only to meet the target of 9–10 million tons of biomass annually by 2030, but also to unlock broader socio-economic benefits rural empowerment, job creation, and local enterprise growth.

In short, biomass co-firing is more than a technical solution. It is a strategic ecosystem project, a collective effort that stitches together diverse actors into a sustainable pathway toward ENDC 2030 and NZE 2060.

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