DINASTI PUBLISHER
DIJEMSS: Dinasti International Journal of Education Management and Social Science
E-ISSN: 2686-6331
P-ISSN: 2686-6358
https://dinastipub.org/DIJEMSS dinasti.info@gmail.com +62 811 7404 455
**DOI:** https://doi.org/10.38035/dijemss.v7i2

# Development of a Biomass Supply Chain Model for Renewable Energy: Preparing for the Green Economy

**Aang Gunawan**[1], **Abdullah Ade Suryobuwono**[2], **Sita Aniisah Sholihah**[3]
[1]Institut Transportasi dan Logistik Trisakti
[2]Institut Transportasi dan Logistik Trisakti
[3]Institut Transportasi dan Logistik Trisakti, avec.sita@gmail.com

Corresponding Author: avec.sita@gmail.com[3]

**Abstract :** Indonesia faces a significant gap in achieving its New and Renewable Energy (NRE) mix target of 23% by 2025. The biomass co-firing program in existing coal-fired power plants (CFPPs) has emerged as a flagship strategy for PT PLN (Persero) to accelerate this transition. However, the program's success is jeopardized by fundamental challenges within the biomass supply chain. The current supply chain is characterized by a fragmented, point-to-point model that has proven inefficient and gives rise to systemic issues, including high logistics costs, supply uncertainty, and a failure of upstream quality control, exemplified by sawdust moisture content frequently exceeding 45%. This research aims to (1) empirically analyze the weaknesses of the existing supply chain at four major CFPPs in Java, (2) design an optimized supply chain framework using a hub-and-spoke model, and (3) develop a techno-economic model for standardizing transportation tariffs. The research methodology integrates field surveys with quantitative modeling, employing a Vehicle Operating Cost (VOC) approach based on Minister of Transportation Regulation No. 60 of 2019 as the foundation for a cost simulator. The analysis confirms that the current point-to-point model is uneconomical due to extreme travel distances (up to 380 km), low asset utilization (50% load factor), and misaligned incentive structures. The proposed hub-and-spoke model is designed for hubs to function as centers for aggregation, pre-processing (drying, densification), quality control (in accordance with SNI 8675:2018), and buffer stocking. The VOC simulation validates the economic feasibility of this model, demonstrating significant cost savings through economies of scale (use of large-capacity trucks) and route optimization. This study concludes that the adoption of a hub-and-spoke model is a strategic prerequisite for the sustainability of the co-firing program. Policy recommendations include the implementation of a pilot project, the restructuring of procurement contracts based on the VOC model, and government incentives for hub development.

**Keywords:** Biomass Supply Chain, Co-firing, Hub-and-Spoke Model, Vehicle Operating Cost (VOC), Biomass Logistics, Renewable Energy

# INTRODUCTION

## The Strategic Imperative for Biomass Supply Chain Optimization in Indonesia's Energy Transition

Indonesia stands at a critical juncture in its energy transition, driven by a national policy mandate to enhance energy security and reduce greenhouse gas emissions. The National Energy Policy (KEN), established through Government Regulation (PP) No. 79 of 2014, sets ambitious targets for the share of New and Renewable Energy (NRE) in the national primary energy mix, aiming for a minimum of 23% by 2025 and 31% by 2050.[1] The National Energy General Plan (RUEN) further operationalizes these targets, providing a strategic roadmap for cross-sectoral implementation (T&E, 2025). However, the realization of these targets faces significant hurdles. A performance report from the Directorate General of NRE and Energy Conservation (EBTKE) at the Ministry of Energy and Mineral Resources (ESDM) revealed that the actual NRE mix in 2023 reached only 13.2%. This creates a substantial gap that must be closed to meet the 2025 goal, demanding the acceleration of programs that can be implemented rapidly and with relatively low capital investment (Paper, 2023).

In this context, the biomass co-firing program at existing coal-fired power plants (CFPPs) has become a cornerstone of PT PLN (Persero)'s strategy. Co-firing, the simultaneous combustion of biomass with coal, is a globally recognized transitional strategy that leverages existing, capital-intensive power generation infrastructure to reduce emissions without the need for constructing new plants.[3] This approach, dubbed the "Green Booster" by PLN, is seen as an effective bridging solution that can be deployed at scale, with a target to implement co-firing at 52 CFPP locations, requiring an estimated 10.2 million tons of biomass annually by 2025.[1] The success of this nationally strategic program is fundamentally contingent on the availability of a sustainable, high-quality, and cost-competitive biomass supply.

This dependency, however, exposes the program's primary vulnerability: a nascent and profoundly inefficient biomass supply chain. Unlike coal, which is a concentrated resource, biomass possesses inherent characteristics that complicate its logistics, including low energy density, high moisture content, and geographically dispersed sources (Viklund, 2013). These challenges are exacerbated by Indonesia's high national logistics costs, which were recorded at 14.29% of the Gross Domestic Product (GDP) in 2022, significantly higher than in neighboring countries. The current supply chain, identified through extensive field surveys, operates on a fragmented, *point-to-point* model. This ad-hoc system has proven to be inefficient, leading to systemic problems such as supply uncertainty, extreme variability in feedstock quality, and an opaque, unstandardized transportation pricing structure.

This situation presents a strategic paradox: a "green" energy initiative designed to be a low-cost, quick-win solution is being systematically undermined by an economically unsustainable and carbon-intensive logistics system. The intended low-capital advantage on the power generation side is being eroded by unaddressed high operational costs and systemic failures on the supply chain side. The environmental benefits of utilizing biomass are partially offset by the emissions from long and inefficient truck journeys, with documented transport distances reaching up to 380 km and load factors as low as 50% due to empty return trips. Therefore, the absence of a structured, economically viable, and scalable supply chain model has become a critical bottleneck, threatening the success of the co-firing program and, by extension, the achievement of the 2025 national NRE target.

This research addresses this critical gap by proposing a fundamental transformation of the biomass supply chain. It aims to: (1) critically analyze the weaknesses of the existing biomass supply chain based on empirical data from four major CFPPs in Java; (2) design an optimized supply chain framework using a hub-and-spoke model; (3) develop and apply a transparent techno-economic model for standardizing transportation tariffs based on national regulations; and (4) provide data-driven policy recommendations to stakeholders to facilitate the national implementation of the proposed model. This study argues that transforming the supply chain from an ad-hoc arrangement into an integrated system is not merely an operational optimization but a strategic prerequisite for the success of Indonesia's energy transition.

## METHOD

This research employs a multifaceted methodological approach that integrates a comprehensive literature review, empirical field surveys, and quantitative modeling to develop a holistic solution for the biomass supply chain challenge (Mohammad S. Roni et al., 2017). The research process was structured into three primary phases. The first phase involved an in-depth literature review of biomass supply chain models and techno-economic analyses, alongside primary data collection through surveys at eleven CFPPs, with a focused analysis on four key sites in Java: Pelabuhan Ratu, Suralaya, Paiton, and Adipala. The second phase centered on modeling and simulation, where the hub-and-spoke supply chain framework was designed and a transportation cost simulator was developed using the Vehicle Operating Cost (VOC) approach. The final phase involved the integration and analysis of simulation results, the formulation of policy recommendations, and the development of draft Standard Operating Procedures (SOPs) and contract designs.

## RESULTS AND DISCUSSION

### Biomass Supply Chain: Unique Challenges and Quality Standards

The biomass supply chain presents unique challenges that distinguish it significantly from conventional fossil fuel supply chains. Biomass is a distributed resource (*nonpoint source*) characterized by low energy density, high quality variability, and often significant moisture content. These factors contribute to the complexity and high cost of collection, pre-processing, storage, and transportation (Hasan et al., 2025).

The quality of biomass feedstock is a critical factor that directly influences boiler efficiency, operational performance, and power plant reliability. Key quality parameters such as moisture content, ash content, and calorific value have direct operational impacts. High moisture content, for instance, significantly reduces the net calorific value, as a substantial portion of thermal energy is consumed to evaporate water, thereby lowering the boiler's thermal efficiency. Furthermore, an unsuitable ash composition, particularly high concentrations of alkali metals (such as Potassium, K) and chlorine (Cl), can lead to severe operational problems like slagging (the formation of molten ash in the boiler radiation zone) and *fouling* (the buildup of ash deposits in the convection zone). These phenomena impede heat transfer and can cause corrosion of boiler tubes (Eunomia, 2016; Taler et al., 2009).

To address these quality challenges, standardization is paramount. National and international standards provide a clear framework for quality assurance. In Indonesia, the primary reference is the Indonesian National Standard (SNI). Specifically, **SNI 8675:2018 on Biomass Pellets for Energy** establishes quality requirements for pellets used in both household and industrial sectors. Key specifications include a minimum net calorific value of 16.5 MJ/kg, a maximum moisture content of 10-12%, and a maximum ash content of 5%.[1] Additionally, SNI 8021:2020 provides more detailed specifications for wood pellets, one of the most common forms of densified biomass. At the international level, the **ISO 17225 series on Solid Biofuels** serves as the global standard for classifying and specifying various forms of solid biofuels, including pellets, briquettes, and wood chips. Adherence to these standards is crucial for facilitating international trade and ensuring quality interoperability between suppliers and end-users. Compliance with these standards is a prerequisite for ensuring efficient and reliable co-firing operations (Kemen ESDM RI, 2024).

## The Hub-and-Spoke Model as an Optimization Framework

To overcome the inherent logistical challenges of the biomass supply chain, the hub-and-spoke model is adopted as the theoretical optimization framework. This model, which originated in the airline and logistics industries, functions by consolidating flows from numerous dispersed source points (*spokes*) to a central facility (*hub*) for processing, storage, and redistribution in larger, more efficient volumes.[7] This structure contrasts sharply with the inefficiency of direct point-to-point networks by leveraging economies of scale on consolidated flows.

In the context of biomass, this model is particularly relevant. Small-scale and geographically scattered biomass producers (e.g., farmers, sawmills, agro-industries) act as the *spokes*, delivering raw materials to a strategically located *hub* at the center of a supplier cluster (Watters & Hayes, 2023). The hub serves not merely as an aggregation point but as a value-adding center with four critical functions:

1. Aggregation: Collecting small volumes from numerous suppliers into large, commercially viable lots.
2. Pre-processing and Quality Control: Performing activities such as drying, chipping, or densification (pelletizing/briquetting) to increase energy density and standardize quality according to established standards (e.g., SNI 8675:2018).
3. Storage: Creating a buffer stock to guarantee supply continuity to the CFPP and mitigate risks associated with seasonality or other supply disruptions.
4. Optimized Dispatch: Consolidating shipments into large-capacity trucks with full payloads for delivery to the CFPP, thereby maximizing transportation efficiency.[1]

This approach directly addresses the primary challenges of the biomass supply chain by creating economies of scale in both transportation and processing, ensuring consistent quality, and enhancing overall supply security. Beyond its logistical benefits, this framework also serves as a significant catalyst for rural economic development. The establishment of hubs in rural areas, at the center of supplier clusters, creates localized industrial ecosystems. This formalizes employment, valorizes what was previously considered agricultural or forestry waste, and stimulates local entrepreneurship in biomass processing. By creating a stable market and a new revenue stream for rural communities, the hub-and-spoke model transforms a national energy initiative into a powerful tool for achieving broader socio-economic development goals.

## Techno-Economic : Vehicle Operating Cost (VOC)

The financial viability of the hub-and-spoke model depends on a transparent and standardized costing mechanism. The methodology adopted in this research is the **Vehicle Operating Cost (VOC)** approach, known in Indonesia as *Biaya Operasional Kendaraan (BOK)*.[11] The framework for this approach is formally detailed in **Minister of Transportation Regulation No. 60 of 2019 concerning the Provision of Freight Transport by Motor Vehicles on Roads**. The use of a framework grounded in national regulation ensures that the developed cost simulator is not arbitrary but possesses a strong, defensible legal basis, making it a credible tool for tariff negotiations and policy formulation.

The VOC model provides a comprehensive decomposition of costs, dividing them into two main categories:

A. **Fixed Costs:** These are costs that do not vary with distance traveled or volume transported. They include vehicle depreciation, licensing and administrative fees (e.g., taxes, KIR roadworthiness tests), insurance, and overhead costs such as non-operational staff salaries and rent for offices and garages.
B. **Variable (Running) Costs:** These are costs directly proportional to operational activity.

They encompass fuel, lubricants, tires, maintenance and spare parts, driver wages or commissions, and other trip-related expenses like tolls and parking fees.

While this regulatory model provides an indispensable and transparent foundation for standardizing transport tariffs, its practical application must acknowledge real-world complexities. Field research identified "hidden costs," such as illegal levies (*pungutan liar*) on certain long-haul routes, which are real expenses for transporters but are not captured in the formal model.[1] Therefore, the VOC framework should be viewed as a powerful baseline and negotiation tool rather than an absolute prescription. Its successful implementation requires a contractual framework flexible enough to accommodate verified, location-specific cost factors that may deviate from the standardized model. By integrating the VOC model into the hub-and-spoke framework, this research creates a holistic solution that is not only structurally and logistically sound but also financially transparent and accountable, bridging international logistics theory with national regulatory practice.

### Analysis of Existing Supply Chain Deficiencies: A Four-CFPP Case Study

An in-depth analysis of the existing supply chain at the four case-study CFPPs—Pelabuhan Ratu, Suralaya, Paiton, and Adipala—revealed a series of systemic weaknesses that impede both efficiency and sustainability. Data synthesized from field surveys consistently showed a pattern of recurring problems across all locations, which can be summarized as follows:

A. **Fragmentation and Extreme Transport Distances:** The current supply chain is characterized by a geographically dispersed network of suppliers with no consolidation points. This forces transportation to be conducted on a point-to-point basis from sources that are often extremely distant. For example, the Suralaya CFPP receives biomass shipments from Kayu Agung, Ogan Komering Ilir, a journey of approximately 380 km. Such extreme distances cause transportation costs to become a dominant and disproportionate component of the total biomass cost (Sadaghiani et al., 2023).

B. **Systemic Failure in Quality Control:** One of the most significant findings is the systemic failure of quality control at the source. The prevailing commercial practice of payment based on gross tonnage, without strict penalties for high moisture content, has created a perverse incentive structure. Suppliers are financially rewarded for delivering low-quality, high-moisture biomass. This is not merely an operational oversight but a logical outcome of a flawed system. Visual documentation at the Pelabuhan Ratu and Adipala CFPPs, showing water draining from trucks loaded with sawdust, provides stark evidence of this problem.[1] Moisture content frequently exceeds the acceptable tolerance, often surpassing 45%, which not only reduces combustion efficiency but also poses a risk of damage to boiler equipment. The current control mechanism of rejecting trucks at the CFPP gate is reactive and highly inefficient, resulting in wasted transportation costs and significant supply uncertainty.

C. **Transportation Inefficiency and Low Asset Utilization:** The use of the transportation fleet is far from optimal. A variety of truck types with differing capacities (ranging from 6 to 30 tons) operate without efficient route planning. Furthermore, most routes are dedicated, meaning trucks return to their point of origin empty. This results in a *load factor* of only 50%, which effectively doubles the contribution of fixed costs to the total cost per ton of biomass transported.

D. **Hidden Costs and Negative Social Impacts:** The current supply chain is also burdened by unforeseen costs. The study identified the presence of illegal levies on some long-haul routes, such as those from Sumatra to Suralaya, adding to cost uncertainty. Additionally, there are negative social externalities, such as dry sawdust blowing from uncovered trucks and disturbing local communities. This has led to the suboptimal practice of wetting the cargo before shipment to reduce dust, a practice that is ironically in direct conflict with the CFPP's need for dry fuel.

To provide a clear comparative overview, Table 1 summarizes the profiles and primary challenges of the biomass supply chains at the four case-study CFPPs.

**Table 1. Profile of Existing Biomass Supply Chains at Case-Study CFPPs**

| CFPP | Primary Biomass Type | Key Supplier Locations | Transport Distance (Min-Max, km) | Dominant Truck Capacity (tons) | Identified Key Challenges |
|---|---|---|---|---|---|
| Pelabuhan Ratu | Sawdust, Rice Husk | Lebak, Banten | 59 - 78 | 6 | Low quality (high moisture), seasonal supply of rice husk |
| Suralaya | Sawdust, Waste | Serang, Lebak, Tasikmalaya, Ogan Komering Ilir | 22 - 384 | 9 - 30 | Extreme distances, high transport costs, illegal levies, unstable supply |
| Paiton | Sawdust | Malang, Lumajang, Jember, Banyuwangi, Probolinggo | 42 - 165 | 6 - 8 | Dependence on furniture industry waste, potential supply competition |
| Adipala | Sawdust, Waste Currency | Banyumas, Banjarnegara, Kebumen, Yogyakarta | 25 - 172 | 6 - 30 | Low quality (high moisture), unstable supply from small industries |

Source: Data Analysis from

This table effectively demonstrates that the problems encountered are not isolated incidents but rather symptoms of structural weaknesses in the existing supply chain model. This builds a compelling case for a fundamental system redesign.

## Design and Application of an Optimized Hub-and-Spoke Framework

In response to the identified systemic deficiencies, this research proposes a structured supply chain framework based on the hub-and-spoke model. This model is designed to introduce efficiency, standardization, and reliability into the system by fundamentally realigning incentives and optimizing logistics. The implementation is based on a zoning strategy and a clear division of roles.

The hub model inherently corrects the misaligned incentives that plague the current system. By introducing a new intermediary—the hub operator—it creates a market entity whose profitability is directly tied to enforcing quality standards. The hub operator will purchase raw biomass from suppliers (*spokes*) and sell standardized, quality-assured biomass to the CFPP. The contract between the hub and the CFPP will be based on strict quality specifications (e.g., moisture content, calorific value). Consequently, the hub is economically incentivized to become the quality gatekeeper. It will implement testing and payment schemes for its own suppliers that penalize high moisture and reward high quality, effectively shifting the quality control process upstream and aligning the financial incentives of the entire supply chain.

### Distance-Based Zoning Strategy (Ring Network Logistics)

Recognizing that a single flat-rate tariff (FOB CFPP) is both unfair and uneconomical given the extreme variation in supplier distances, the proposed model adopts a zoned tariff approach. Based on an analysis of supplier distances to the CFPP, several concentric zones or "rings" are defined, each with a specific radius. Each zone will have a distinct tariff structure that fairly reflects the associated transportation costs. This strategy creates a more predictable market structure and encourages logistical efficiency at every level.

### Definition of Roles in the Hub-and-Spoke Model

The new structure defines clear roles for each actor in the supply chain:

A. **Spokes (Collection Points):** These are the upstream raw material suppliers, such as farmers, forest farmer groups, sawmills, and agricultural processing industries. Their primary role is to collect raw biomass and transport it to the nearest hub. The key advantages for them are short, predictable transport distances and a guaranteed buyer (*off-taker*) at the hub.

B. **Hubs (Consolidation and Pre-processing Centers):** These are strategically located facilities at the center of supplier clusters. The hub functions as the heart of the model, performing the four key value-adding functions previously described: aggregation, quality control and pre-processing, storage, and optimized dispatch.

### Quantitative Cost Analysis and Simulation Results

To validate the economic feasibility of the proposed model, a quantitative cost analysis was conducted using the VOC simulator developed based on Minister of Transportation Regulation No. 60 of 2019. The simulator utilized input parameters obtained from field surveys, including average truck speeds on different road types (arterial, local), fuel consumption rates, and vehicle carrying capacities, to generate realistic cost estimates.

The simulation results consistently highlighted three primary factors influencing transportation cost efficiency:

1. **The Impact of Distance:** The analysis revealed a critical paradox: while the cost per ton-kilometer (Rp/Ton-Km) tends to decrease with increasing distance (due to the amortization of fixed costs over more kilometers), the total cost per ton (Rp/Ton) increases significantly. For instance, a simulation for the Kawalu to Suralaya CFPP route (384 km) yielded a VOC of Rp 464/Ton-Km, which is much lower than the Rp 1,798/Ton-Km for the shorter Padarincang to Suralaya CFPP route (61.3 km). However, the total cost per ton for the longer route was Rp 178,219, whereas the shorter route cost only Rp 110,270 per ton. This confirms that transporting low-value, raw biomass over very long distances is uneconomical. The hub-and-spoke model resolves this by breaking the journey into two stages: an inexpensive, short-haul trip from the spoke to the hub, followed by an efficient, long-haul transport of a higher-value, densified product from the hub to the CFPP.
2. **The Impact of Vehicle Capacity (Economies of Scale):** The simulation unequivocally demonstrated significant economies of scale associated with the use of larger-capacity trucks. On the Buayan to Adipala CFPP route (43.7 km), the transportation cost per ton using a 30-ton capacity truck was calculated at Rp 37,578. This figure nearly doubled to Rp 62,313 per ton when using a 16-ton capacity truck.[1] This finding strongly reinforces the justification for the hub's role as a consolidation point, where smaller loads from spokes can be aggregated for transport to the CFPP using maximum-capacity fleets.

3. **The Impact of Load Factor:** The analysis underscored the drastic inefficiency caused by the prevailing 50% load factor (empty return journeys). Assuming fixed costs constitute a significant portion of total costs, an empty return trip effectively doubles the allocation of fixed costs to each ton of biomass transported. The hub-and-spoke model enables better route planning, including the potential for *backhauling* (return loads) or triangular routes, which could increase the load factor to near 100%. A scenario for the Suralaya CFPP, involving long-haul routes with a 100% load factor, showed the potential for substantial cost savings compared to dedicated, short-haul routes.

This quantitative data provides compelling evidence that the strategic optimization achieved through the hub-and-spoke model is not merely an incremental improvement but a fundamental transformation capable of yielding substantial cost savings. This provides a solid basis for PLN and policymakers to restructure biomass procurement contracts and tariffs.

## CONCLUSION

The comprehensive analysis of the biomass supply chain for Indonesia's co-firing program leads to the conclusion that the current operational model is unsustainable and represents a primary barrier to achieving national energy targets. The ad-hoc, point-to-point supply chain has been shown to generate high logistics costs, inconsistent feedstock quality, and supply uncertainty, which collectively threaten the economic and operational viability of the co-firing program.

Conversely, this research demonstrates that the adoption of a structured hub-and-spoke model combined with a zoned tariff system based on the transparent Vehicle Operating Cost (VOC) methodology, offers a systematic, efficient, and economically feasible solution. Quantitative analysis through simulation has confirmed that logistics optimization through load consolidation, the use of larger-capacity vehicles, and an increased load factor can lead to significant reductions in transportation costs.

Based on these findings, a series of actionable policy recommendations are formulated for key stakeholders:

**For PT PLN Energi Primer Indonesia:**

A. **Implement a Pilot Project:** Immediately launch a pilot project to fully implement the hub-and-spoke model at a single CFPP, ideally the Suralaya CFPP. This location is recommended due to its diverse and challenging supply routes, which would serve as a valid proof-of-concept for the model before a national rollout.

B. **Restructure Procurement Contracts:** Transition from the current single FOB (Free On Board) pricing scheme to a dynamic, zoned tariff structure based on the validated VOC cost calculator. New contracts must include stringent quality clauses referencing SNI/ISO standards, with clear penalty mechanisms for deviations in critical parameters like moisture content and calorific value.

C. **Forge Strategic Partnerships for Hub Development:** Proactively establish partnerships with the private sector, state-owned enterprises (BUMN), or Village Unit Cooperatives (KUD) to invest in the development of biomass hubs at strategic locations. PLN can act as a long-term off-taker to provide the investment security necessary for these partners.

**For Government Regulators (Ministry of Energy and Mineral Resources and Ministry of Transportation):**

A. **Formalize a Standard Transportation Tariff:** Adopt and formalize the VOC-based cost calculator developed in this study as a national reference for determining biomass transportation tariffs. This step will create a transparent and predictable market, which is essential for attracting private investment.

B. **Provide Incentives for Hub Development:** Create fiscal incentives, such as tax relief or investment grants, for the construction of biomass hub facilities. These facilities should be officially recognized as critical infrastructure supporting the national energy transition.

C. **Simplify Regulations:** Pursue deregulation and simplification of the licensing processes related to the collection, processing, and transportation of biomass to reduce bureaucratic barriers and lower administrative costs.

**For Future Research:**

A. **Life Cycle Assessment (LCA):** Conduct a comprehensive LCA of the entire hub-and-spoke supply chain, from harvesting to combustion, to accurately measure the net carbon footprint and ensure that the environmental benefits of co-firing are fully realized.

B. **Multimodal Logistics Integration:** Develop models to integrate rail and sea transportation, which will be crucial for inter-island supply chains, particularly for supplying CFPPs in regions with limited local biomass resources.

C. **Techno-Economic Analysis of Advanced Pre-processing:** Conduct in-depth techno-economic feasibility studies on integrating advanced pre-processing technologies, such as torrefaction, at the hub level. Torrefaction can significantly increase the energy density of biomass, potentially leading to drastic reductions in final-leg transportation costs.

Ultimately, the successful implementation of this model requires a paradigm shift from the often-antagonistic, transactional relationships between PLN and its suppliers to a collaborative ecosystem approach. Synergy is required among PLN as the buyer, private investors as hub operators, local communities as suppliers, and the government as a regulatory facilitator. Only through such an integrated partnership can an efficient and sustainable biomass supply chain be realized, which will, in turn, form the backbone of a successful energy transition in Indonesia.

## REFERENCES

Abusaq, Z., Habib, M. S., Shehzad, A., Kanan, M., & Assaf, R. (2022). A Flexible Robust Possibilistic Programming Approach toward Wood Pellets Supply Chain Network Design. *Mathematics*, *10*(19). https://doi.org/10.3390/math10193657

Afandi, A. S., & Pohan, G. A. (2023). Karakteristik Pembakaran Wood Pellet Kayu Sengon. *Jurnal Teknik Mesin Institut Teknologi Nasional Malang*, 1–7.

Ahmudi, A., Hudaya, C., Garniwa, I., Amraini, S. Z., Sugiyono, A., Semedi, J. M., Sidqi, M. A., Daulay, A. D. K., & Yumnaristya, S. H. (2025). Optimizing Potential Supply Chain of Biomass Agricultural Waste for Co-firing of Coal Power Plant Using MCDA, GIS, and Linear Programming in the Java and Sumatra Islands, Indonesia. *Leuser Journal of Environmental Studies*, *3*(1), 1–19. https://doi.org/10.60084/ljes.v3i1.249

Alpian, A., Rivaldi, Wahyu Supriyati, Luhan, G., & Surasana, I. N. (2023). Karakteristik Pelet Kayu Laban (Vitex Pubescens) Sebagai Bahan Bakar Alternatif Terbarukan. *Jurnal Penelitian Hasil Hutan*, *41*(1), 27–34. https://doi.org/10.55981/jphh.2023.679

Aslani, L., Hasan-Zadeh, A., Kazemzadeh, Y., & Sheikh-Azadi, A. H. (2024). Design of a sustainable supply chain network of biomass renewable energy in the case of disruption. *Scientific Reports*, *14*(1), 1–18. https://doi.org/10.1038/s41598-024-64341-9

BUFFHAM, M., HUNT, S., PERERA, D., & ZAMAN, P. (2024). *Bioenergy Series-How Is Forest Biomass Affected By Red Iii? APRIL 2024*, 4. https://eur-lex.europa.eu/legal-content/AUTO/?uri=CELEX:32018L2001&qid=1710508036699&rid=1

Cahyo, N., Sulistiyowati, D., Rahmanta, M. A., Felani, M. I., Soleh, M., Paryanto, P., Prismantoko, A., & Hariana, H. (2024). A techno-economic and environmental analysis of co-firing implementation using coal and wood bark blend at circulating fluidized bed boiler. *International Journal of Renewable Energy Development*, *13*(4), 726–735. https://doi.org/10.61435/IJRED.2024.60234

de Jong, S., Hoefnagels, R., Wetterlund, E., Pettersson, K., & Junginger, M. (n.d.). Optimizing biofuel supply chains based on liquefaction technologies – the hub and spoke model. *Prepared for Submission*, 8–9.

Directives, T. E. U. (2010). *EU sustainability criteria for biofuels*. *September 2017*, 2–3.

Ernawati, L., Ginting, R. R., Lestari, R., Raihan, M., Sianturi, H. G. P., Kurniawati, D. M., Amrullah, A., Farobie, O., & Prawisudha, P. (2025). Pengolahan Sampah Padat Tpas Manggar Menjadi Produk Biopellet (Refuse-Derived Fuel) Dengan Mesin Pelletizer Berbasis Sistem Penggerak Roller. *JMM (Jurnal Masyarakat Mandiri)*, *9*(3), 2912. https://doi.org/10.31764/jmm.v9i3.31314

Eunomia. (2016). *Drivers of Growth and Cost Changes in European Renewable Heat Technologies*. *January*. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/498970/European_deployment_of_RHts_Phase_2__FInal_Report_DECC_Template_V4_.pdf

European Commission DG Mobility and Transport. (2015). *Analysis of recent trends in EU shipping and analysis and policy support to improve the competitiveness of Short Sea Shipping in the EU*. *June*. http://ec.europa.eu/transport/modes/maritime/studies/doc/2015-june-study-sss-final.pdf

Hasan, M., Zada, M., & Pan, D. (2025). *A Comprehensive Systematic Review of Dynamic Nutrient Profiling for Personalized Diet Planning : Meta-Analysis and PRISMA-Based Evidence Synthesis*.

Herianto, Santoso, M., Simatupang, R. Y., Supriyati, W., & Mujaffar, A. (2022). Karakteristik Pelet Serbuk Gergaji Tiga Jenis Kayu Limbah Industri Mebel Sebagai Energi Alternatif Terbarukan. *Hutan Tropika*, *16*(2), 164–174. https://doi.org/10.36873/jht.v16i2.3575

Indonesia. (2023). *Tata Cara Penyusunan Rencana Umum Energi Daerah*. *No. 73 Tahun 2023*, 1–25.

Kemausuor, F., Bolwig, S., & Miller, S. (2016). Modelling the socio-economic impacts of modern bioenergy in rural communities in Ghana. *Sustainable Energy Technologies and Assessments*, *14*, 9–20. https://doi.org/10.1016/j.seta.2016.01.007

Kemen ESDM RI. (2024). *Capaian Kinerja Sektor Esdm Tahun 2023 Dan Target 2024*. 1–35.

Kementerian Perhubungan. (2019). Peraturan Menteri Perhubungan Republik Indonesia No.60 Tahun 2019 tentang Penyelenggaraan Angkutan Barang dengan Kendaraan Bermotor di Jalan. *Kementerian Perhubungan*, *1*(1), 116.

Kementrian ESDM. (2023). Laporan Kinerja DITJEN EBTKE. *Http://Kemdikbud.Go.Id/*, *4*(Mei), 197. https://www.menpan.go.id/site/publikasi/unduh-dokumen-2/akuntabilitas-kinerja/laporan-kinerja/file/6647-laporan-kinerja-lakip-2021

Kurniawan. (2019). BAB II Tinjauan Pustaka BAB II TINJAUAN PUSTAKA 2.1. 1–64. *Gastronomía Ecuatoriana y Turismo Local.*, *1*(69), 5–24.

Li, S., Tan, E. C. D., Dutta, A., Snowden-Swan, L. J., Thorson, M. R., Ramasamy, K. K., Bartling, A. W., Brasington, R., Kass, M. D., Zaimes, G. G., & Hawkins, T. R. (2022). Techno-economic Analysis of Sustainable Biofuels for Marine Transportation. *Environmental Science and Technology*, *56*(23), 17206–17214. https://doi.org/10.1021/acs.est.2c03960

Lien, S. K., Taxt, H., & Lindbeg, B. (2023). Transition Towards Low-Carbon. *Sustainability Report*.

Onyenwoke, C., Tabil, L. G., Dumonceaux, T., Mupondwa, E., Cree, D., Li, X., & Onu Olughu, O. (2024). Technoeconomic Analysis of Torrefaction and Steam Explosion Pretreatment Prior to Pelletization of Selected Biomass. *Energies*, *17*(1), 1–19. https://doi.org/10.3390/en17010133

Paper, P. (2023). *european bioplastics Sustainability Criteria for Biomass*. *2413*, 1–5.

Pemerintah Republik Indonesia. (2014). Peraturan Pemerintah Republik Indonesia No.79 Tahun 2014 Tentang Kebijakan Energi Nasional. *Kementerian Sekretariat Negara Republik Indonesia*, 1–60.

Penrusunan, B. M. (2023). *Tahun 2023 iv Indeks Pembangunan Manusia ......._._ Prioritas Nasional 4 Prioritas Nasional 6. 218005*.

Preview, T. S. (2021). *Solid biofuels-Fuel specifications and classes-Part 1: General requirements Biocombustibles solides-Classes et spécifications des combustibles-Partie 1: Exigences générales(E) ii COPYRIGHT PROTECTED DOCUMENT. 2021*. www.iso.org

Qian, Y., & McDow, W. (2013). The wood pellet value chain: An economic analysis of the wood pellet supply chain from the Southeast United States to European Consumers. *US Endowment for Forestry and Communities*, *March*, 59. http://www.usendowment.org/images/The_Wood_Pellet_Value_Chain_Revised_Final.pdf

*Renewables*. (2025).

Roni, M. S., Cafferty, K. G., Hess, J. R., Jacobson, J. J., Kenney, K. L., Searcy, E., & Tumuluru, J. S. (2016). Lignocellulosic crop supply chains (eg, Miscanthus, switchgrass, reed canary grass, rye, giant reed, etc.). In *Biomass Supply Chains for Bioenergy and Biorefining* (Issue February). Elsevier Ltd. https://doi.org/10.1016/B978-1-78242-366-9.00012-5

Roni, Mohammad S., Eksioglu, S. D., Cafferty, K. G., & Jacobson, J. J. (2017). A multi-objective, hub-and-spoke model to design and manage biofuel supply chains. *Annals of Operations Research*, *249*(1–2), 351–380. https://doi.org/10.1007/s10479-015-2102-3

Sadaghiani, S., Mafakheri, F., & Chen, Z. (2023). Life Cycle Assessment of Bioenergy Production Using Wood Pellets: A Case Study of Remote Communities in Canada. *Energies*, *16*(15). https://doi.org/10.3390/en16155697

Setya Permatasari, C., Fahrizki, J., & Sasongko, N. A. (2019). Bioenergy power generation improved through biomass co-firing-a viewpoint of Life Cycle Assessment (LCA) method. *IjoLCAS*, *3*, 33–40.

Standards, B. (n.d.). *Can / Csa-Iso Solid Biofuels*. *3*, 2–4.

Surya, V. A., & Wijanarko, D. V. (2024). Pengaruh Perekat Tapioka terhadap Kualitas Biopelet dari Campuran Tongkol Jagung, Ampas Tebu, dan Ampas Kopi. *Jurnal Teknik Mesin*, *12*(02), 39–44.

T&E. (2025). *The e-SAF market: Europe's head start and the road ahead. June*.

Taler, J., Trojan, M., & Taler, D. (2009). Assessment of ash fouling and slagging in coal fired utility boilers. *International Conference on Heat Exchanger Fouling and Cleaning VIII*, *2009*, 103–112.

Tenaga, M., Dan, K., Republik, T., Tenaga, K., Dan, K., & Fungsi, D. A. N. (2010). *Republik Indonesia Republik Indonesia*. *2013*(021), 1–266.

Tortosa-Masiá, A., Ahnert, F., Spliethoff, H., Loux, C., & Hein, K. (2005). Slagging and fouling in biomass co-combustion. *Thermal Science*, *9*(3), 85–98. https://doi.org/10.2298/tsci0503085t

Viklund, P. (2013). *Superheater corrosion in biomass and waste fired boilers Characterisation , causes and prevention of chlorine-induced corrosion*.

Visser, L., Hoefnagels, R., & Junginger, M. (2020). Wood pellet supply chain costs – A review and cost optimization analysis. *Renewable and Sustainable Energy Reviews*, *118*(November), 109506. https://doi.org/10.1016/j.rser.2019.109506

Watters, A., & Hayes, P. (2023). *Canada Wood Pellet Annual. July 2022*, 1–17. https://fas.usda.gov/data/canada-canada-wood-pellet-annual

Zhu, D., Yang, H., Chen, Y., Li, Z., Wang, X., & Chen, H. (2017). Fouling and slagging characteristics during co-combustion of coal and biomass. *BioResources*, *12*(3), 6322–6341. https://doi.org/10.15376/biores.12.3.6322-6341