EVERGREEN - Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 13, Issue 01, pp. 18-44, March, 2026

A System Dynamics Approach to Evaluating Biomass-Coal Co-Firing in Indonesia: An Integrated Technical, Economic, Environmental, and Social Framework

Rahmi Kartika Jati[1,*], Sik Sumaedi[2], Sih Damayanti[2], Mahmudi[3],
Igif Gimin Prihanto[3], Marlina Pandin[1], Hendy Gunawan[3], Medi Yarmen[1],
Mauludin Hidayat[4], Agung Widyo Utomo[1], Nurfadlih Syahlani[1],
Nidya J. Astrini[2], Anggini Dinaseviani[5], Aris Yaman[6]

[1]Research Center for Sustainable Industrial and Manufacturing Systems, Research Organization for Energy and Manufacture, National Research and Innovation Agency, South Tangerang, Indonesia
[2]Research Center for Behavioral and Circular Economics, National Research and Innovation Agency, Jakarta, Indonesia
[3]Research Center for Public Policy, National Research and Innovation Agency, Jakarta, Indonesia
[4]Research Center for Manufacturing Technology, National Research and Innovation Agency, South Tangerang, Indonesia
[5]Research Center for Economics of Industry, Services, and Trade, National Research and Innovation Agency, Jakarta, Indonesia
[6]Research Center for Artificial Intelligence and Cyber Security National Research and Innovation Agency Bandung, Indonesia

*Author to whom correspondence should be addressed:
E-mail: rahm030@brin.go.id

(Received May 26, 2025; Revised September 24, 2025; Accepted December 16, 2025)

Abstract: This study employs a qualitative System Dynamics (SD) methodological approach, utilizing stakeholder workshops and interviews, to investigate the evaluation structure of biomass and coal co-firing integration in Indonesia's coal-fired power plants. The primary deliverable of this research is a validated conceptual model that serves as the foundation for a dynamic simulation framework and a subsequent policy roadmap. A key novel finding is the identification and stakeholder validation of specific feedback mechanisms unique to Indonesia's archipelagic context, including four reinforcing loops (R1-R4)—such as policy-driven cost efficiency tied to local subsidy schemes—and one critical balancing loop (B1) representing technical and supply chain bottlenecks, like feedstock variability. This Indonesia-centric SD framework structures the dynamic interactions between policy, economics, and logistics, accounting for constraints such as fragmented supply chains and regional disparities. It enables the testing of six tailored policy interventions, including incentives for biomass utilization, subsidy schemes for co-firing infrastructure, and carbon pricing. The resulting conceptual model and policy roadmap provide stakeholders with a practical tool for optimizing co-firing strategies to support Indonesia's journey toward its net-zero emissions goal.

Keywords: Biomass; Co-Firing; Emissions Reduction; Indonesia; System Dynamics

1. Introduction

As an archipelagic nation experiencing rapid economic and population growth, Indonesia's escalating energy demands are predominantly fueled by coal, a resource central to powering its industrial expansion and urbanization. In 2023, coal made up 34.83% of the nation's energy source consumption.[1)], underscoring its critical role in Indonesia's fossil fuel-dependent economy. However, this reliance on coal has significant environmental consequences, particularly in terms of greenhouse gas (GHG) emissions, which have prompted Indonesia to commit to decarbonization under the Paris Agreement.[2)].

Cite: R. Jati et al., "A System Dynamics Approach to Evaluating Biomass-Coal Co-Firing in Indonesia: An Integrated Technical, Economic, Environmental and Social Framework". Evergreen, 13 (01) 18-44 (2026). https://doi.org/10.5109/7405126.

To achieve its targets of a 23% renewable energy mix by 2025 and net-zero emissions by 2060, Indonesia has initiated biomass co-firing in its coal-fired power plants.[3]. Prior studies confirm biomass co-firing's viability in archipelagic contexts but lack dynamic modeling of Indonesia's unique supply chain fragmentation and policy feedback loops[4,5]. This study addresses this gap by integrating spatial logistics (e.g., Java-Kalimantan disparities) and subsidy-driven cost efficiency loops critical for net-zero pathways. This strategy aims to transition the energy sector toward sustainability while maintaining energy security and socio-economic benefits.

Biomass co-firing offers a promising solution to Indonesia's dual challenges of energy security and environmental sustainability[6–8]. Indonesia's abundant biomass, estimated at 130 million tons or 39 million tons oil equivalent (Mtoe), represents a significant energy potential[7]. Biomass, sourced from organic waste materials such as crop residues, wood industry by-products, and other plant-based remnants, is classified as carbon-neutral due to its closed carbon cycle: the carbon dioxide emitted during its combustion is equivalent to the amount absorbed by the plants during their photosynthetic growth phase. Compared to coal, biomass contains lower levels of sulfur and nitrogen, resulting in reduced emissions of sulfur oxides (SO_x) and nitrogen oxides (NO_x). Additionally, its high volatile matter-to-fixed carbon ratio enhances combustion efficiency, making it a viable alternative fuel for coal power plants[9,10]. In contrast to coal, biomass exhibits distinct variations in its physical structure, chemical composition, and energy density. These variations demand specialized pretreatment processes such as torrefaction or pelletization to enable seamless integration with conventional energy infrastructure[9,11].

While biomass co-firing offers promise for Indonesia's energy transition, its adoption faces multifaceted barriers. To ensure viability, a robust supply chain—spanning sustainable feedstock cultivation, logistical coordination, and preprocessing stages—is indispensable. Additionally, upgrading existing coal power infrastructure to accommodate biomass combustion requires substantial capital expenditure and advanced technical proficiency to achieve seamless operational integration. Community acceptance is also crucial in mitigating potential social and environmental conflicts. Recognizing these challenges, the Indonesian government has developed a roadmap to scale up biomass consumption, projecting an increase from 0.25 million tons in 2021 to 10.2 million tons by 2025 [12]. This shift is expected to reduce annual CO_2 emissions by 11.58 million tons while promoting rural development through job creation and poverty alleviation in biomass supply chains[13,14].

However, a critical gap persists in system-level evaluations that can model the dynamic, non-linear feedback characteristic of Indonesia's archipelagic context. Existing research (2019–2024) predominantly isolates technical feasibility[6,7,15,16] or environmental benefits[13,17,18], often relying on static methodologies, such as Life Cycle Assessment (LCA) or linear optimization. While effective for evaluating static cost-emission trade-offs[19], these approaches are limited in their ability to capture complex causal linkages—such as how logistical bottlenecks in Java dynamically escalate transport costs over time or the lagged impact of subsidy policies on adoption rates. Consequently, they fail to model the dynamic interdependencies among socio-economic, policy, and technical dimensions, a limitation that is acute in Indonesia, where supply chain fragmentation and spatial disparities dominate. Furthermore, despite system dynamics (SD) applications in energy transitions globally[20,21], its use for modeling Indonesia's co-firing ecosystem remains unexplored.

This study presents Indonesia's first stakeholder-validated System Dynamics (SD) framework, specifically designed to capture the dynamic interdependencies and nonlinear feedbacks arising from its unique archipelagic context. The novel framework explicitly models causal relationships between Indonesia-specific variables—addressing critical gaps in (1) dynamic interdependencies, (2) policy feedback loops, and (3) spatial logistics—such as spatially fragmented feedstock supply chains, regionally divergent retrofit costs, and policy implementation delays. By moving beyond static or isolated analyses, this holistic tool enables the simulation of time-dependent interactions across technical, economic, and social dimensions, thereby providing a robust foundation for optimizing co-firing strategies in support of Indonesia's net-zero emissions goal.

The primary objectives are to develop Indonesia's first stakeholder-validated causal loop diagram (CLD) capturing unique archipelagic feedback structures, identify output indicators, and derive Indonesia-specific policy interventions for evaluating biomass and coal co-firing as a foundation for quantitative implementation. To address the stated objectives, this research formulates the following questions to provide a focused and structured framework for analysis:

- ❖ O1: To map the causal feedback structure of Indonesia's biomass-coal co-firing system via a stakeholder-validated Causal Loop Diagram (CLD).
- ❖ O2: To identify and define key output indicators for assessing co-firing effectiveness.
- ❖ O3: To identify critical implementation barriers from stakeholder input.
- ❖ O4: To propose and prioritize policy interventions addressing these barriers.
- ❖ These objectives are addressed through the following research questions:
- ❖ RQ1: How do stakeholders perceive the causal relationships between input and output indicators

in evaluating biomass and coal co-firing?

- RQ2: What output indicators can represent the effectiveness of biomass and coal co-firing processes?
- RQ3: What practical implementation barriers do stakeholders identify?
- RQ4: What policy interventions need to be undertaken to address the barriers?

2. Literature Review

2.1. Biomass and Coal Co-firing Technology

Co-firing, which integrates biomass with coal in conventional coal-based power infrastructure, has gained recognition as a viable strategy to mitigate carbon emissions by leveraging Indonesia's extensive biomass reserves while maintaining existing energy generation frameworks[22]. This technology offers significant environmental benefits by reducing the carbon intensity of electricity generation, as the biogenic carbon released during biomass combustion is considered carbon-neutral[23]. In addition, studies have demonstrated its potential to enhance fuel flexibility and reduce operational costs[24,25]. However, integrating biomass into coal-fired power plants presents unique challenges, including variations in biomass quality, retrofitting costs, and logistical issues. To address these challenges and optimize co-firing systems, researchers are advancing several methodologies:

- Thermochemical Pretreatment: Techniques like torrefaction, hydrothermal carbonization (HTC), or hydrothermal upgrading aim to improve biomass properties (e.g., increasing energy density, reducing moisture, homogenizing composition) for easier handling and more efficient combustion[26,27].
- Multi-Criteria Optimization Frameworks: Goal-oriented algorithms are employed to balance economic and environmental objectives systematically. These frameworks integrate variables such as feedstock specifications, logistical constraints, preprocessing demands, energy yield efficiency, and costs to find solutions that minimize both financial expenditures and ecological footprints[28,29].

The findings indicate that it is essential to carefully manage the blend ratios of biomass and coal to ensure acceptable fuel properties and optimize the benefits of co-firing. In conclusion, co-firing technology presents a promising solution for reducing greenhouse gas emissions in the power sector by incorporating renewable biomass resources into coal-fired power generation[30,31].

2.2. Co-firing Effectiveness Metrics

Evaluating the effectiveness of co-firing requires a multidimensional approach that considers technical, environmental, economic, and social factors. Key technical factors include generation capacity, which is critical as it reflects the maximum power output of the plant under co-firing conditions[18,32,33]. The net power generation heat rate, which measures the efficiency of converting fuel energy into electricity, is another essential factor, as it directly impacts operational costs and emissions[33–35]. Power plant efficiency is closely tied to these metrics, as it determines the overall effectiveness of the co-firing process[32,36]. Additionally, the furnace exit gas temperature (FEGT) is a key operational parameter, as it influences combustion stability and emissions[37,38]. Total fuel consumption and specific fuel consumption (SFC) provide insights into the fuel efficiency of the system, while the biomass-to-coal ratio determines the proportion of renewable energy in the fuel mix[37–39]. The properties of biomass—such as moisture, ash, and carbon composition—significantly affect combustion performance and emissions. The biomass calorific value, in particular the High Heating Value (HHV), is crucial for assessing the energy contribution of biomass relative to coal[37,40,41]. Operational flexibility, fuel availability and security, emissions control, and life cycle assessment (LCA) are other important factors. Operational flexibility reflects the plant's ability to adapt to varying biomass and coal inputs.

Key environmental factors for evaluating biomass and coal co-firing include the CO_2 intensity of electricity[42–44] and the CO_2 intensity of the economy [42,44,45], which measure emissions relative to energy output and economic activity. CO_2 emissions [29,46] and net GHG emissions [46–49] are critical for assessing climate impact, while the global warming potential (GWP) reduction[50] quantifies the mitigation potential. Other factors include electricity generated, water footprint, and the calorific value of lignite[35,50,51]. Emissions of N_2O and soil GHG emissions reflect additional environmental impacts, while soil loss rates in arable lands highlight land-use concerns [47,52]. Compliance with emission limits for SO_x, NO_x, and particulate matter[53] ensures regulatory adherence. Finally, annual GHG emissions and carbon footprint provide comprehensive measures of environmental performance. These factors collectively enable a robust evaluation of the ecological sustainability of co-firing.

Key economic factors for evaluating biomass and coal co-firing include the carbon price, which reflects broader economic impacts[53]. Power plant capacity determines scalability, while biochar yield, fuzzy biochar limit, and sequestration factor assess co-benefits such as carbon sequestration[47]. The production cost of biomass fuel pellets influences feedstock affordability, while investment indicators and energy cost indicators provide insights into capital and operational expenditures[33,50]. A pivotal benefit of co-firing lies in its capacity to retrofit pre-existing coal combustion facilities for biomass integration, thereby eliminating the need for substantial financial commitments toward new infrastructure development[24,54]. This strategy facilitates an economically viable transition to a sustainable energy matrix by optimizing existing power generation infrastructure and grid systems, thereby minimizing capital outlays while aligning with decarbonization objectives. These factors collectively determine the economic feasibility and sustainability of co-firing systems.

Key social factors for evaluating biomass and coal co-firing include land-use issues and the distances between biomass sources and power plants, which affect logistics and community impact[47]. Land use and land influence environmental and social trade-offs, while diversity and development reflect broader socio-economic benefits[33,55]. Potential job creation in biomass and community engagement highlights opportunities for local development[56,57]. A good green image, high social acceptance, and social responsibility are critical for public support, while local zoning laws ensure regulatory compliance[57,58]. These factors collectively determine the social feasibility and community impact of co-firing systems.

The evaluation of co-firing requires a holistic approach that integrates technical, environmental, economic, and social factors. Technically, key factors such as generation capacity, power plant efficiency, and biomass-to-coal ratio ensure operational feasibility and performance. Environmentally, metrics such as CO_2 intensity, net GHG emissions, and reduction in global warming potential highlight the system's ability to mitigate climate impacts. Economically, factors such as carbon price, maintenance costs, and cost-effectiveness determine financial viability, while job creation, social acceptance, and community engagement underscore the social benefits and challenges. In summary, Indonesia's co-firing initiative utilizes domestic biomass to reduce the carbon footprint of its coal-intensive electricity sector. References note that this strategy is enabled by policy mandates and the harnessing of diverse biomass resources[59].

2.3. System Dynamics in Renewable Energy Research

System Dynamics (SD) has been widely used to analyze complex energy systems, particularly in renewable energy transitions such as co-firing[60–62]. SD models can simulate policy incentives, biomass adoption, emissions reduction, and operational constraints limiting biomass use in biomass and coal co-firing. SD has also been widely applied to other renewable energy systems, offering a broader context for its utility. For example, SD models have been used in offshore wind power to analyze the effectiveness of subsidy policy scenarios[21]. In coal-fired power plants, SD calculates the cost of coal using a user approach and assesses economic and environmental performance under various tax scenarios[20]. A recent example of sustainable development's application in energy policy is its role in designing subsidy policies for the coal-to-gas project[63]. Within Southeast Asia, emerging studies highlight the utility of SD for tackling regional energy challenges. For example, research in Vietnam has utilized SD to model the economic viability of rice straw co-firing, capturing feedback between feedstock pricing, farmer incentives, and policy support[64]. Meanwhile, studies in the Philippines have applied SD to optimize carbon management networks for biomass co-firing[47].

SD offers distinct advantages over conventional methods such as Life Cycle Assessment (LCA), linear optimization, and econometrics by addressing their key limitations. While LCA provides static emission accounting, it fails to capture behavioral and market[39,65,66]. SD fills this gap by modeling dynamic policy adoption pathways. Linear optimization excels at cost-emission trade-offs but assumes linear relationships, limiting its ability to represent real-world disruptions[67–69]. Econometric models are useful for analyzing historical trends but lack the flexibility for forward-looking scenario testing of unprecedented policy interventions.

The unique strength of SD lies in its capacity to model time-lagged policy impacts (e.g., the delay between subsidy introduction and widespread adoption) and critical feedback loops (e.g., how biomass price hikes might reduce usage, thereby stabilizing prices). This capability is precisely what is needed to navigate Indonesia's spatially fragmented energy landscape, where non-linear dynamics dominate—such as Java's logistics bottlenecks versus Kalimantan's seasonal feedstock abundance. By simulating how changes in one domain (e.g., a new subsidy) cascade through technical, economic, and social systems over time, SD provides an integrative approach essential for robust decision-making in Indonesia's complex energy transition, effectively balancing short-term actions with long-term decarbonization outcomes.

2.4. Biomass and Coal Co-Firing in Indonesia

Following the Paris Agreement, Indonesia aims to raise the share of renewable energy in its energy mix to 23% by 2025. Fossil fuels comprise 87% of the national energy mix, with coal contributing 65%. To counter this dependence on fossil fuels and lower carbon emissions, the Indonesian State Electricity Company (PLN) initiated a co-firing program that integrates biomass with coal in 52 coal-fired power plants (PLTU). This initiative aims to improve existing infrastructure while contributing to Indonesia's long-term goal of achieving net-zero emissions by 2060[12].

The biomass co-firing program demonstrates significant variation in energy capacity and biomass requirements throughout Indonesia (Table 1). While 35 of 52 targeted plants adopted co-firing by 2022, implementation varies

Table 1: Summarizes PLN's co-firing progress (2021–2023) and regional disparities

Region	Plants Operational (2023)	Capacity (GW)	Biomass Used (kTon/yr)	Key Challenges
Java	16/16	14.8	4,920	None (mature supply chain)
Sumatra	9/13	1.8	1,450	High transport costs (30% above Java)
Kalimantan	5/8	1.2	980	Feedstock seasonality
Sulawesi	2/6	0.4	310	Limited preprocessing facilities
Nusa Tenggara	3/9	0.3	190	Low biomass collection efficiency

Source: PLN Sustainability Reports (2023)[70)]

sharply due to the very interdependencies this study aims to model:

- Java dominates, achieving high efficiency due to integrated supply chains.
- Sumatra and Kalimantan face higher costs from decentralized sourcing.
- Eastern Indonesia lags due to limited infrastructure and lower collection rates[70)].

These regional disparities validate the need for the spatially explicit feedback loops (e.g., B1) in the conceptual model, as costs and constraints are not uniform nationally, directly addressing RQ3 by highlighting location-specific implementation barriers. The variation in key challenges—from mature supply chains in Java to feedstock seasonality in Kalimantan and logistical inefficiencies in Eastern Indonesia—creates a patchwork of distinct subsystems within the national program. This context highlights the need for a modeling approach like System Dynamics, which can simulate how policies tailored for one region (e.g., pre-processing subsidies in Sulawesi) may yield different outcomes than those in another (e.g., transport cost support in Sumatra). The Indonesian case, therefore, presents an ideal and compelling application for an SD framework to inform effective, context-sensitive policy.

3. Methodology

This study employs a qualitative System Dynamics (SD) approach to develop a conceptual framework for evaluating biomass-coal co-firing in Indonesia. The primary outputs of this research are a stakeholder-validated Causal Loop Diagram (CLD) and a set of policy recommendations. The methodology is designed to address the following core objectives:

- To map the causal feedback structure of the biomass-coal co-firing system in Indonesia (addressed in Section 4.1).
- To identify key output indicators for assessing co-firing effectiveness (addressed in Section 4.3).

To identify and suggest policy interventions to overcome implementation barriers (addressed in Section 4.4).

The SD methodology was selected over alternatives, such as Life Cycle Assessment (LCA) or linear optimization, due to its unique capacity to model the dynamic interdependencies and nonlinear feedback loops inherent in Indonesia's archipelagic energy transition. As established in the literature review, static methods are unable to capture critical dynamics, such as time-lagged policy impacts, spatially fragmented supply chain disruptions, or the feedback between social acceptance and investment. SD is uniquely suited to address RQ1 (causal relationships) and RQ3 (implementation barriers) by making these complex, circular causalities explicit.

3.1. Research Design

This research is designed as a qualitative SD study, focused on the initial conceptualization phase of model building. The core activity was the participatory development and validation of a Causal Loop Diagram (CLD) that represents the key feedback structures governing the biomass-coal co-firing system in Indonesia. This conceptual model serves as the necessary foundation for future quantitative simulation.

3.2. Data Collection

Data was collected from various sources to ensure triangulation and build a comprehensive understanding of the co-firing system.

3.2.1. Stakeholder Engagement and Selection

Purposive sampling techniques were used to identify and engage nine key experts from industry and utilities who are direct actors in Indonesia's co-firing ecosystem. The focus on this stakeholder group was due to their in-depth knowledge of the technical, economic, and supply chain challenges that were the primary focus of the study. The participants consisted of plant managers, operational engineers, and strategic planners from steam power plants (PLTU) that have implemented or are currently implementing co-firing programmes.

3.2.2. Data Collection Protocols

Semi-structured interviews were conducted using a pre-defined protocol. The discussions focused on eliciting mental models regarding causal relationships (RQ1), perceived effectiveness metrics (RQ2), and critical barriers (RQ3).

Structured Data Templates: To ensure consistency and comparability, a standardized data collection template was used to gather technical, economic, environmental, and social parameters from power plant reports and policy documents. This template, provided in Appendix A, includes predefined fields for over 40 indicators (e.g., generation capacity, heat rate, transport costs, job creation estimates).

Secondary Data Review: A systematic review of academic literature (via Scopus and Web of Science), Indonesian government policy documents (e.g., PLN Sustainability Reports, MEMR decrees), and technical reports from power plants was conducted to supplement and validate primary data.

3.3. Analytical Procedure: Causal Loop Diagram (CLD) Development

The development of the CLD was an iterative process involving three primary steps, as outlined below:

Step 1: Variable Identification. Key variables influencing the co-firing system were identified and categorized from the transcribed workshop discussions, interviews, and secondary data. These variables were mapped onto the standardized template in Appendix A to ensure comprehensive coverage across technical, economic, environmental, and social dimensions.

Step 2: Loop Mapping and Diagramming. Causal links between the identified variables were established based on stakeholder narratives and evidence from the literature. The polarity of each link (positive [+] or negative [-]) was determined. These links were then assembled into reinforcing (R) and balancing (B) feedback loops that describe the core dynamics of the system, such as "Policy-Driven Cost Efficiency" (a reinforcing loop) and "Technical/Supply Chain Constraints" (a balancing loop).

Step 3: Stakeholder Validation. The preliminary CLD was presented back to the stakeholders in a second validation workshop. Their feedback was used to refine the loops, confirm causal relationships, and ensure the model accurately reflected the on-the-ground realities of Indonesia's co-firing initiative. This step was crucial for establishing the model's face validity and practical relevance.

3.4. Data Validation and Triangulation

To ensure the reliability and validity of the findings, a rigorous triangulation protocol was applied, as detailed in Appendix B. Every central data point (e.g., policy parameter, technical cost, social impact) was cross-verified against at least three independent sources:

i. Primary Source: Direct measurement or stakeholder claim.
ii. Secondary Source: Official reports (e.g., PLN operational data).
iii. Tertiary Source: Academic literature or third-party analysis.

This multi-source validation mitigates bias and enhances the credibility of the conceptual model.

4. Result

4.1. Conceptual Model Development

This section presents the primary conceptual output of the study: a stakeholder-validated Causal Loop Diagram (CLD) developed through the qualitative System Dynamics (SD) methodology outlined in Section 3. The CLD serves as the foundational model that captures the dynamic interdependencies between technical, economic, environmental, and social variables governing Indonesia's biomass-coal co-firing system. The structure of this model, including its variables and the feedback loops (R1-R4, B1), is grounded in the synthesis of the literature review (Section 2) and, crucially, the empirical input from stakeholder workshops and interviews. The SD approach was selected precisely for its unique capacity to map these non-linear, time-delayed feedback structures, which static methods like Life Cycle Assessment (LCA) cannot capture, thus providing a holistic framework essential for policy design in Indonesia's complex, archipelagic context. The main processes for evaluating biomass and coal co-firing in Indonesia. The primary processes include:

4.1.1. Fuel Substitution

Fuel substitution refers to replacing coal with biomass to achieve a cleaner and sustainable energy source[71,72]. Torrefied biomass is a viable alternative due to its improved properties after undergoing torrefaction, a thermal treatment to improve the chemical and physical characteristics[73]. Torrefied biomass has better grindability, making it compatible with coal in existing power plant systems without requiring substantial infrastructure modifications[74]. Medium-temperature torrefied biomass (MTTB) has a Hardgrove Grindability Index (HGI) similar to that of coal, enabling co-milling with coal for use in co-firing processes[75,76].

Co-firing torrefied biomass with coal offers environmental benefits. Blending 50% torrefied biomass with 50% coal results in stable combustion while reducing emissions. Studies have shown that compared to coal combustion alone, nitrogen oxide (NOx) emissions can be reduced by as much as 30% and sulfur oxide (SOx) emissions can decrease by up to 50%[74]. These mitigation efforts are crucial in addressing the ecological challenges associated with coal-based energy generation, which significantly contributes to atmospheric greenhouse gas concentrations. Moreover, torrefied biomass emits lower amounts of pollutants compared to raw biomass and coal[77,78]. This aligns with the model's goal of reducing carbon emissions while ensuring energy security and sustainability. Another advantage of using torrefied biomass in co-firing is its potential to alleviate ash-related issues.

4.1.2. Cost-Efficiency

The conceptual framework for biomass-coal co-firing seeks to minimize operational expenditures while reducing carbon emissions and supporting long-term energy sustainability objectives. Retrofitting existing coal-powered facilities for biomass integration is widely regarded as an economically viable strategy, as it leverages existing infrastructure and avoids the capital-intensive investment required for constructing new renewable energy facilities79). The retrofitting cost is significantly lower than that of building new renewable energy plants39,80). Furthermore, incorporating biomass into coal power plants can reduce reliance on high-cost carbon reduction technologies like Carbon Capture and Storage (CCS) 39,80,81).

Meanwhile, proximity to biomass resources is critical for minimizing transport costs. Studies indicate that decentralized preprocessing facilities can lower logistics expenses. However, converting biomass into torrefied pellets increases its energy density, which reduces transportation costs per unit of energy and enhances overall cost efficiency82). There are also economic benefits from emissions-related savings. Retrofitting coal plants for co-firing can lower expenses tied to carbon taxes or emissions trading83). Co-firing effectively reduces greenhouse gas emissions, serving as a practical short-term measure to cut carbon output while transitioning to long-term renewable energy solutions43). Despite these advantages, achieving cost efficiency demands strategic planning and policy backing. Investments in biomass infrastructure, feed-in tariffs, and carbon pricing mechanisms are essential for enhancing economic feasibility. These policies help offset upfront costs and provide incentives to adopt biomass co-firing technologies39,81).

4.1.3. Social Impact

The societal implications of co-firing are multidimensional, influencing sectors such as job creation, community well-being, and ecological sustainability. Using biomass for energy production can improve local air quality by reducing harmful emissions, including PM2.5 and NOx.64). This is particularly relevant in developing countries like Indonesia, where air pollution from open biomass burning and coal usage poses serious public health risks. The reduction of these pollutants not only enhances the quality of life but also reduces health issues in local communities64). Moreover, job creation is a crucial facet of the social impact. Biomass energy systems generate more employment opportunities in rural areas, particularly in the collection, processing, and transportation of biomass64,84). These employment opportunities can boost economic empowerment in rural areas, helping to reduce poverty.

The socio-economic benefits of biomass co-firing extend to gender equity and inclusive community development85). In rural Indonesia, gender roles in agricultural activities are significantly dominated by men, while women play a more significant role in domestic activities86). To ensure equitable benefit distribution, gender-targeted initiatives—such as skills training in biomass preprocessing, leadership programs for women-led cooperatives, and childcare support—can enhance female participation in the supply chain. By involving women in biomass supply chains, co-firing initiatives can promote gender equity, providing women with economic opportunities and decision-making roles87). Additionally, community engagement protocols must prioritize participatory resource governance, where women and marginalized groups co-design benefit-sharing mechanisms (e.g., job creation, revenue allocation for local schools, healthcare)84). Failure to address these dimensions risks reinforcing socioeconomic disparities and undermining community acceptance of co-firing projects.

Community acceptance and participation are also essential for the success of biomass projects and for ensuring the fair distribution of benefits and costs to build community trust and support84). Local communities should experience tangible benefits, such as job opportunities and improved local air quality, while minimizing excessive drawbacks, including noise and other environmental concerns. Additionally, confidence in institutional stakeholders and transparent decision-making processes is needed to overcome resistance84). Moreover, biomass co-firing initiatives have the potential to promote social equity by addressing energy access disparities88). The traditional use of biomass in rural households poses health risks and limits economic opportunities, particularly for women and children involved in fuel collection. Transitioning to structured biomass energy systems can alleviate these burdens, improve indoor air quality, and allow for better allocation of time for education and other productive activities, thus enhancing overall social development89).

4.1.4. Sustainability

The sustainability of biomass and coal co-firing is based on its potential to balance environmental protection, economic viability, and energy security. Compared to coal combustion, co-firing helps lower greenhouse gas emissions, thereby reducing the environmental impact of power generation90–92). Co-firing also decreases emissions of pollutants like CO_2, SO_2, and NO_x, making it a vital strategy for transitioning to cleaner energy while ensuring grid reliability93). Biomass co-firing supports sustainable development goals by utilizing local renewable resources such as agricultural residues and forest waste18). This approach reduces reliance on coal, a finite resource, while supporting rural economies through job creation. Furthermore, it promotes long-term energy sustainability by curbing fossil fuel use89).

Biomass co-firing can even result in harmful emissions when combined with technologies like biochar production and soil carbon sequestration. This dual function—generating energy and acting as a carbon sink—highlights its role in sustainable energy strategies[47].

However, the sustainability of biomass co-firing depends on resolving logistical challenges such as biomass collection, transportation, and storage, which can affect efficiency and cost. The establishment of robust policy frameworks and targeted financial mechanisms is critical to overcoming existing barriers and enhancing the viability of biomass-based energy initiatives within Indonesia's renewable energy transition[94]. Collaboration across sectors and public-private partnerships is necessary to build a strong biomass supply chain, reduce operational challenges, and encourage broader adoption[94]. Policy support plays a key role in expanding biomass co-firing. Governments can facilitate sustainability by providing subsidies, tax incentives, and carbon pricing mechanisms that encourage investment in renewable energy technologies. Such measures can help achieve a balanced energy mix while adhering to international commitments to reduce greenhouse gas emissions[95].

4.1.5. Emission Reduction

The potential of reducing emissions through biomass and coal co-firing is supported by its impact on lowering greenhouse gas (GHG) emissions and other pollutants[96]. Integrating biomass into coal combustion processes capitalizes on its inherent carbon neutrality, as biogenic CO_2 released during energy production is offset by photosynthetic carbon uptake during biomass growth. This co-firing approach significantly cuts GHG emissions from coal-fired power plants by reducing CO_2, SO_x, and NO_x outputs. These reductions result from the lower sulfur and nitrogen content in biomass compared to coal, along with enhanced combustion efficiency through optimized operational adjustments[97,98]. Depending on the biomass blend ratio and type, co-firing can reduce emissions by up to 46% compared to burning coal alone[99]. In Malaysia, using palm oil biomass in co-firing reduces CO_2 emissions by approximately 8.83 million tons per year, demonstrating the clear environmental benefits of integrating biomass into existing energy systems[99,100]. Life Cycle Assessment (LCA) studies show that substituting 10% of coal with biomass in thermal power systems results in a 9% reduction in total GHG emissions, due to the replacement of fossil carbon with biogenic carbon cycles during combustion[19].

Using torrefied biomass further enhances these benefits by improving combustion efficiency and reducing particulate emissions[101]. Co-firing biomass in a swirl-stabilized furnace lowers NOx and SOx emissions, making it an effective strategy for reducing air pollution from coal-fired power plants[19]. Additionally, applying advanced technologies like oxy-fuel combustion can amplify these reductions by enabling carbon capture and further decreasing GHG emissions during combustion[102,103]. However, the extent of emissions reduction depends on variables such as biomass quality, pre-treatment processes, and co-firing ratios.

To maxim ize environmental benefits, it is essential to optimize the biomass supply chain—including collection, transportation, and preprocessing—to ensure that emissions from operations do not outweigh the gains from co-firing[82].

Stakeholder validation confirmed that these feedback structures, particularly the balancing loop B1 (Technical/Supply Chain Constraints) driven by high moisture variability in tropical biomass and the reinforcing loop R1 (Policy-Driven Cost Efficiency) reliant on specific Indonesian subsidy mechanisms, represent dynamics uniquely critical and pronounced within Indonesia's archipelagic co-firing ecosystem, differing significantly from feedback observed in more centralized systems. Based on the following identified main processes, as shown in Figure 1, the proposed causal loop diagram (CLD) outlines key relationships:

4.1.5.1. Reinforcing Loops (R)

R1 (Policy-Driven Cost Efficiency): Subsidies (e.g., torrefaction infrastructure grants) reduce operational costs, incentivizing higher biomass use → greater economies of scale (e.g., 30% cost reduction in decentralized preprocessing hubs in Sumatra[14,39,82]).

R2 (Social Impact): Job creation in biomass collection (e.g., 500+ roles in Kalimantan's rice-husk supply chains[64,70,84]) boosts community support → accelerated project approvals.

R3 (Sustainability): Reduced coal dependency (e.g., 10% substitution in Pangkalan Susu PLTU[70]) lowers emissions → stronger policy backing for renewable targets.

Consistent with prior study, independent biomass suppliers show lower sustainability barriers (e.g., no land-clearing emissions)[5]. However, our model reveals integrated PLN plants face stronger balancing loops (B1) due to feedstock variability—a dynamic unseen in cluster studies[5].

R4 (Emission Reduction): CO_2 offsets (e.g., 11.58M-ton annual reduction by 2025[12]) meet regulatory standards → expanded co-firing mandates.

4.1.5.2. Balancing Loop (B)

B1 (Technical/Supply Chain Constraints): Feedstock variability (e.g., moisture fluctuations in Java's woodchips[9,39]) increases retrofitting costs → limits biomass ratios (e.g., capped at 20% in PCB boilers[18]).

Reinforcing loops (R1-R4) align with the prior study[5]: Policy-driven cost efficiency (R1) mirrors Indonesian subsidy mechanisms, while social impact loops (R2) reflect job creation in biomass supply chains (e.g., 500+

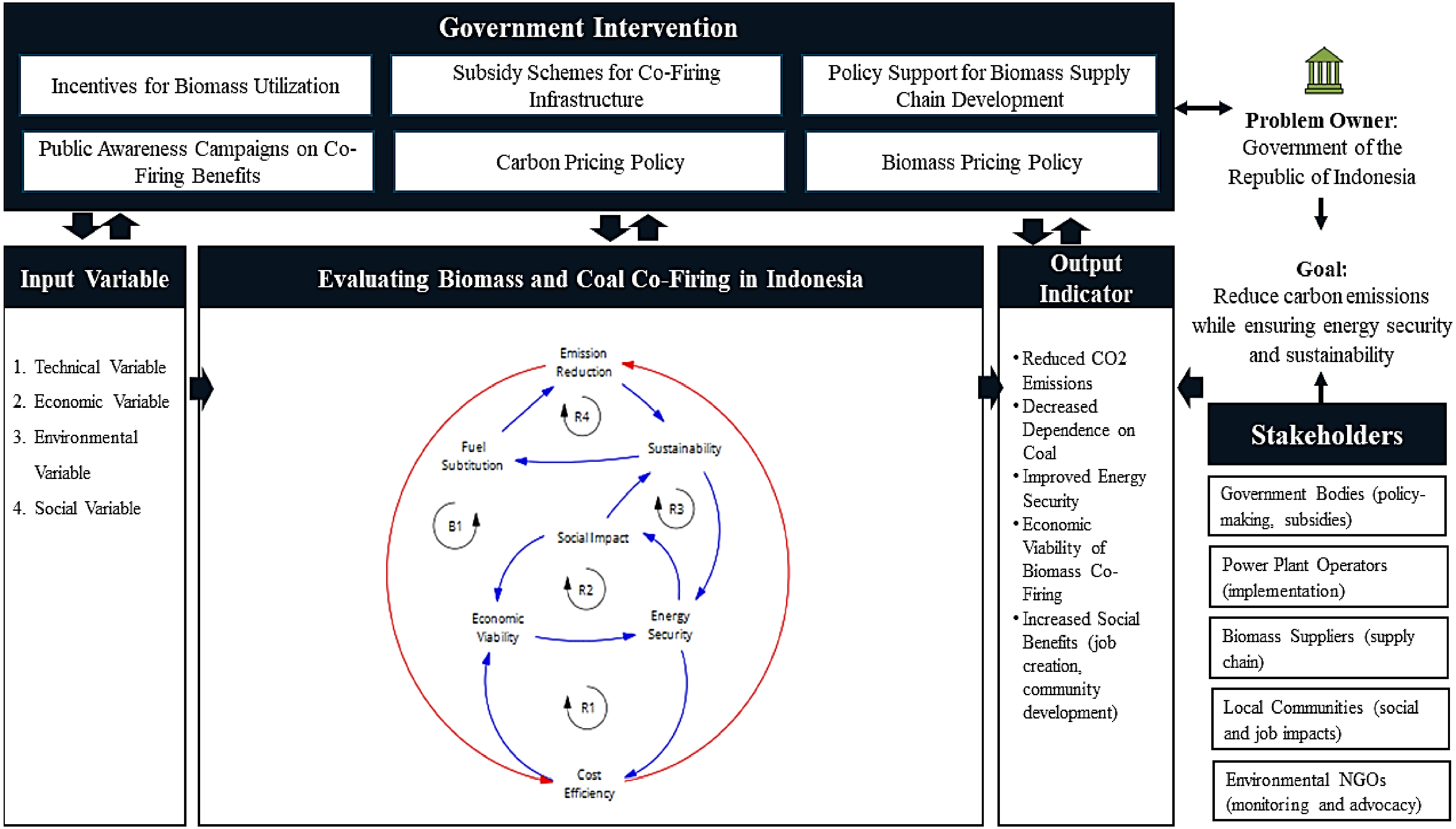

Fig. 1: Conceptual Model for Evaluating Biomass and Coal Co-firing in Indonesia: Input variables (technical, economic, environmental, social) drive core feedback loops (e.g., R1–R4, B1). Outputs include CO_2 reduction, decreased dependency on coal, energy security, economic viability, and social benefits. Arrows denote causal relationships. The CLD explicitly maps the causal relationships perceived by stakeholders (RQ1), illustrating how reinforcing loops (R1-R4) can drive adoption while balancing loop B1, which captures critical technical and supply chain barriers (RQ3). Source: *Author's own work*

Table 2: Roadmap for Operationalizing Conceptual Model for Evaluating Biomass and Coal Co-firing in Indonesia

Phase	Activities	Objective	System Component	Model Linkage	Deliverables	Implementation Strategy	Practical Outcomes
Phase 1 Model Structuring & Boundary Definition	Identify key feedback loops Define model boundary and subsystems- Map policies to loops	Define system boundary and align structure with policy objectives	Government Interventions	Maps policy levers to feedback loops (R1 and B1)	- Preliminary CLD - Stakeholder policy influence map	Map interventions to specific feedback loops: - Carbon pricing → R1 (Cost Efficiency) - Biomass pricing → B1 (Supply Chain Stability)	Policy Optimization Design policy mechanisms that amplify virtuous loops Clear alignment of carbon pricing with emission reduction goals in simulations
Phase 2 Data Collection & Parameter Estimation	Gather tech, economic, social, and environmental data Regional differentiation of inputs Estimate biomass ratios and transport costs	Quantify variables to enable baseline and scenario simulations	Input Variables	Inputs function as levers in “what-if” simulations	- Baseline database - Regional input matrix - Assumptions list	Technical: Torrefaction tech → ↑ biomass ratio Social: Community engagement → ↓ implementation time	Scenario Customization: Customize co-firing design by province or plant type
Phase 3 Model Calibration & Validation	Simulate baseline case Compare outputs to LCA/PLN data Get expert/stakeholder feedback	Test the internal consistency and predictive power of the tax rollout model	Core Processes	Validates loops R1–R4 (emissions, cost, logistics, labor)	- Calibrated simulation model - Validation report - Error bounds	Emission Reduction: % biomass co-firing = % CO_2 ↓ Cost Efficiency: Decentralized preprocessing → ↓ % transport cost	Operational Targets Predict CO_2 impact of % co-firing scenarios
Phase 4 Scenario Testing & Policy Simulation	Define and simulate scenarios Analyze trade-offs (emission, cost, labor) Visualize alternative futures	Simulate the impact of policies, technology mixes, and market changes	Output Indicators	Uses output indicators to evaluate trajectories (2025–2060)	- Policy scenario report - Recommendation brief - Emissions reduction trajectory map	Reduced CO_2 by year Social Benefits: jobs/tons of biomass	Net-Zero Roadmap Test different co-firing growth rates and incentives
Phase 5 Stakeholder Engagement & Implementation Design	Co-develop accountability matrix Align KPIs with national roadmap Build dashboards for feedback loops	Translate model insights into roles, KPIs, and policy tools	Stakeholders	Embeds KPIs into actor mandates (Govt, PLN, communities)	- Stakeholder responsibility map - Biomass contract clauses (e.g., % local labor) - Monitoring dashboard	Government: Monitor policy compliance via indicators Communities: Job creation KPIs in biomass contracts	Accountability Matrix Link incentives and penalties to co-firing performance Biomass contracts include local job clauses; PLN monitored on CO_2 targets

This roadmap operationalizes the conceptual model by translating causal loops (R1–R4, B1) into a phased implementation strategy, directly addressing RQ4 by providing a clear pathway for policymakers to test and implement the proposed interventions. Source: Author's own work

Cite: R. Jati et al., "A System Dynamics Approach to Evaluating Biomass-Coal Co-Firing in Indonesia: An Integrated Technical, Economic, Environmental and Social Framework". Evergreen, 13 (01) 18-44 (2026). https://doi.org/10.5109/7405126.

roles in Kalimantan). Balancing loop B1 models feedstock variability constraints identified in PLN case studies (Section 4.1).

Addressing RQ1, stakeholders perceived the dynamics of fuel substitution as nonlinear (Figure 1, Loop B1).

Technical constraints—including feedstock variability and retrofitting costs—were identified as critical balancing forces that limit biomass-to-coal ratios (RQ3). Stakeholder consultations identified three critical barrier categories impeding co-firing implementation:

Technical barriers center on biomass heterogeneity, which necessitates costly torrefaction (increasing operational expenses) and introduces slagging/fouling risks at co-firing ratios. Technical barriers (e.g., torrefaction costs) confirm the previous finding that transport optimization reduces expenses by 43%4). Economic hurdles (supply chain fragmentation) echo the prior study's emphasis on localized preprocessing to mitigate Java-Kalimantan cost disparities5).

Economic constraints are dominated by transport costs from decentralized sources and the absence of co-firing-specific subsidies.

Socio-political challenges include land-use conflicts between food and energy crops, alongside regulatory ambiguities in biomass certification that delay investments.

These stakeholder-validated barriers—preprocessing costs, supply chain fragmentation, and regulatory uncertainty—remain critically underexplored in existing literature.

The proposed CLD, illustrated in Figure 1, outlines the key causal relationships and feedback structures. To guide the reader through the model's logic, we detail the mechanisms of one reinforcing loop (R1: Policy-Driven Cost Efficiency) and the critical balancing loop (B1: Technical/Supply Chain Constraints) as representative examples.

- ➢ Reinforcing Loop R1 (Policy-Driven Cost Efficiency): This loop illustrates a virtuous cycle that can accelerate co-firing adoption.
- ➢ It begins with Government Subsidies (e.g., for torrefaction infrastructure), which directly reduce the Operational Costs for power plants.
- ➢ Lower operational costs improve the Cost-Efficiency of co-firing, making it a more attractive investment and leading to increased Biomass Utilization.
- ➢ Higher adoption rates drive Economies of Scale in the biomass supply chain (e.g., through the establishment of decentralized preprocessing hubs), which further reduces biomass fuel costs and reinforces the initial improvement in Cost-Efficiency.
- ➢ This creates a self-reinforcing cycle (denoted by the 'R'): supportive policy lowers costs, which encourages adoption, which in turn makes the technology even more cost-effective, leading to further policy support and adoption.

Balancing Loop B1 (Technical/Supply Chain Constraints): This loop represents a critical limiting factor that counteracts growth.

- ➢ An increase in the target Biomass-to-Coal Ratio drives higher demand for biomass feedstock.
- ➢ However, in Indonesia's context, this increased demand encounters Feedstock Variability (e.g., high and fluctuating moisture content in tropical biomass) and logistical bottlenecks.
- ➢ These challenges increase Retrofitting and Maintenance Costs (e.g., to handle different biomass properties, address slagging, or expand storage facilities) and create Supply Chain Disruptions.
- ➢ The rising costs and operational uncertainties act as a balancing force, ultimately limiting the feasible Biomass-to-Coal Ratio and constraining further growth. This negative feedback mechanism (denoted by the 'B') ensures the model captures the real-world constraints that prevent exponential expansion.

The other loops function similarly:

- ➢ R2 (Social Impact): Job creation from biomass supply chains boosts Community Support, leading to smoother Project Approvals and further biomass utilization.
- ➢ R3 (Sustainability): Reduced coal dependency lowers Emissions, strengthening Policy Backing for renewables.
- ➢ R4 (Emission Reduction): CO_2 offsets help meet Regulatory Standards, leading to expanded Co-firing Mandates.

Stakeholder validation confirmed that these feedback structures, particularly the pronounced effect of balancing loop B1 driven by high moisture variability in tropical biomass and the reinforcing loop R1, which relies on specific Indonesian subsidy mechanisms, represent dynamics uniquely critical within Indonesia's archipelagic co-firing ecosystem.

4.2. Empirical Lessons from PLN Initiatives

PLN's pioneering co-firing projects across the Indonesian archipelago provide invaluable, real-world lessons on the complexities and potential of integrating biomass into the existing coal fleet. These case studies reveal that success hinges not just on technical feasibility, but critically on local conditions, biomass characteristics, and economic viability. Input Variables PLN's co-firing projects reveal critical insights:

- ➢ Pangkalan Susu PLTU (Sumatra): Rice-husk co-firing at 10% blend reduced CO_2 by 42,000 tons/yr but required 25% higher maintenance due

---

Cite: R. Jati et al., "A System Dynamics Approach to Evaluating Biomass-Coal Co-Firing in Indonesia: An Integrated Technical, Economic, Environmental and Social Framework". Evergreen, 13 (01) 18-44 (2026). https://doi.org/10.5109/7405126.

to slagging[18,38].

- Paiton PLTU (Java): Torrefied wood pellets at 15% blend boosted combustion efficiency by 8% and cut NO_x by 30%[7,14].
- Barru PLTU (Sulawesi): Abandoned 2022 co-firing pilot due to 70 km biomass transport radius exceeding economic viability[70].

PLN's diverse experiences paint a nuanced picture. Co-firing offers a proven route to reduce emissions and utilize local biomass resources. However, the path is not uniform. Biomass Type Matters: Raw agricultural residues can cause operational challenges (slagging, corrosion), increasing maintenance costs. Pre-Processing is Key: Upgrading biomass (e.g., pelletizing, torrefaction) significantly improves efficiency, reduces emissions, and mitigates operational issues. Logistics Define Viability: The economic feasibility is critically dependent on a dense, localized, and cost-effective biomass supply chain; long transport distances can be prohibitive. These empirical lessons directly inform RQ3 by validating the balancing loop B1 (Technical/Supply Chain Constraints), demonstrating how real-world barriers, such as slagging from raw biomass and prohibitive logistics costs, manifest and limit co-firing ratios.

While empirical lessons from PLN’s initiatives show the practical challenges of implementing biomass co-firing, it is essential to compare these findings with broader empirical and policy-oriented studies. Several recent

Table 3: Empirical and Policy Studies Related to Biomass–Coal Co-Firing and System Dynamics Elements

No.	Ref.	Key Findings	Comparison
1	104)	The report examined whether existing biomass waste from agricultural, forestry, and municipal sources can be utilized without causing land use change (LUC). The study also found that co-firing with only waste feedstock gives minimal emissions reduction, and that supply is limited, especially in eastern provinces.	The study supports balancing loop B1 (Technical/Supply Chain Constraints) strongly by supply limits and spatial/seasonal variability. Furthermore, the study also provides comparison points for the emission reductions (R4) and shows that using waste biomass only yields smaller gains unless supply chain and sourcing issues are addressed. This is a useful benchmark for the output indicator “Reduced CO_2 Emissions.”
2	105)	The report found that at current targets (e.g., 10% co-firing), national emission reduction is expected only ~1.5-2.4% for the coal power sector; improvements in NO_x, SO_2, and PM are modest (e.g., 7-10%) under those shares; central technical and monitoring, regulatory, and supply issues remain.	In current R1/R4 loops, we assume that policy, cost efficiency, and other factors can drive substantial growth and emission reductions. The report suggests modest gains without strong interventions. This report can be used as a reference when discussing “how large B1 might constrain reinforcing loops.” Additionally, it is necessary to address the output of “Decreased Dependence on Coal” and social regulatory acceptability barriers.
3	106)	The report observed the following quantitative values: baseline emissions at 0.896 kg CO_2/kWh for coal, reducing to ~0.727 kg CO_2/kWh with 20% wood-pellet co-firing (without CCS). With CCS, substantial reductions, including harmful net emissions in some scenarios, are achieved with a high biomass share. This study also demonstrated how the cost (capital + O&M) increases with the biomass share and CCS retrofit.	Relevant to the current loops R4 (Emission Reduction) and R1 (Cost Efficiency). We can compare the emission reduction magnitudes and cost penalties with what stakeholders perceive as CLD. In addition, these numbers can help calibrate the cost vs emission trade-offs in our scenario testing phase.
4	107)	The report discussed biomass co-firing at low shares (≤5-10%) as the most realistic option in the near term, given technical constraints, biomass quality, transportation, moisture, and cost. In addition, the report showed that biomass properties (lower energy density, higher moisture, variable ash) create both cost and efficiency penalties. Furthermore, the study pointed out policy, regulatory, and technical barriers (feedstock, pre-treatment, etc.).	Matches with B1 barriers; helpful empirical support for technical variable inputs (e.g., moisture, HHV, ash). Moreover, the study supports stakeholder findings about retrofitting costs and supply chain fragmentation as well as to validate balancing constraints.
5	108)	The report conducted a qualitative and CLD-style study, identifying numerous factors (~44) that affect biomass co-firing in Indonesia, including supply variation, fuel quality, regulatory framework, biomass suppliers, energy producers, and government policy. Furthermore, the study emphasizes the importance of coordinated policies, supply chain investment, and stakeholder collaboration.	This study helps validate the CLD loops (R & B), especially reinforcing social loops (R2) and balancing technical/logistical aspects (B1); as well as validating barriers and input variables from stakeholders.

Cite: R. Jati et al., "A System Dynamics Approach to Evaluating Biomass-Coal Co-Firing in Indonesia: An Integrated Technical, Economic, Environmental and Social Framework". Evergreen, 13 (01) 18-44 (2026). https://doi.org/10.5109/7405126.

techno-economic analyses, system dynamics approaches, and environmental impact assessments provide additional perspectives on biomass supply constraints, emission reduction potential, and cost–benefit trade-offs. Table 3 summarizes key studies that reinforce and complement the insights derived from PLN's experience, offering a broader evidence base for evaluating the reinforcing and balancing loops identified in this research.

4.3. Input Variables

The conceptual model for evaluating biomass and coal co-firing in Indonesia identifies four key input variables: technical, economic, environmental, and social. These variables collectively shape the implementation and effectiveness of the co-firing initiative in achieving sustainability and reducing carbon emissions.

The technical variable addresses the challenge of mixing biomass with coal in current power plants. Biomass has different physical and chemical properties compared to coal, including less energy density[109)], higher volatile matter [110)], and reduced sulfur and nitrogen content[111)]. These differences necessitate the development of specialized technologies, such as torrefaction, drying, and pelletization, to enhance the compatibility of biomass with coal systems. For example, the higher volatility of biomass causes efficient combustion[9)]. Moreover, advanced boiler systems, such as Circulating Fluidized Bed (CFB) boilers, are necessary to manage the unique combustion properties of biomass while maintaining operational efficiency[112,113)].

The economic variable focuses on the cost of making the model feasible. Improving existing coal plants to co-fire is a cost-effective alternative to building new renewable energy facilities. This approach has economic benefits, particularly when combined with preprocessing technologies like torrefaction to improve biomass's energy density and reduce transportation costs[39)]. Government actions, such as subsidies and carbon pricing, also help make this initiative financially feasible by reducing initial expenses and offering incentives for the use of biomass co-firing technologies.

The environmental dimension underscores the significant ecological advantages of biomass co-firing. Biomass is classified as carbon-neutral[114)], as the CO_2 emitted during combustion is equivalent to the atmospheric carbon sequestered through photosynthetic processes during its cultivation period. This property supports Indonesia's goals under the Paris Agreement, which aim to reduce greenhouse gas emissions. Additionally, the lower sulfur and nitrogen levels in biomass lead to reduced emissions of SO_x and NO_x [82)]. These benefits are enhanced by the opportunity to use repurposed combustion by-products, such as ash, in agriculture and construction, thereby minimizing waste and supporting circular resource use.

The social variable highlights the broader societal implications of biomass integration, particularly its role in promoting rural development. The biomass supply chain, encompassing collection, preprocessing, and transportation, generates job opportunities in rural areas, contributing to economic growth and poverty reduction. Community involvement is needed to ensure fair sharing of the benefits and costs linked with biomass projects[84)]. Moreover, switching from coal to biomass improves air quality, which in turn boosts public health and reduces the social costs associated with pollution. These input variables form the foundation of the causal relationships in the CLD (RQ1) and directly influence the output indicators defined in RQ2, creating a direct pathway from system inputs to measurable outcomes.

4.4. Output Indicators

To address RQ2, five evidence-based output indicators were established through stakeholder validation and literature synthesis. The Output Indicators focus on the practical and social advantages of incorporating biomass into coal power systems. Furthermore, these indicators are vital for measuring the effectiveness and viability of the co-firing effort.

4.4.1. Reduced CO_2 Emissions

Lowering carbon dioxide (CO_2) emissions is a primary objective of co-firing biomass and coal. By partially substituting coal with biomass, the model leverages the carbon-neutral properties of biomass. The CO_2 emitted during biomass burning is offset by the CO2 taken up during its growth, thereby helping to lower greenhouse gas emissions. Studies show that co-firing can reduce CO2 emissions by up to 46%, depending on the type of biomass and the mixture ratio. For example, an LCA of using wood pellets with coal showed a 9% reduction in greenhouse gases, essential for Indonesia's net-zero emissions target by 2060.

4.4.2. Decreased Dependence on Coal

Co-firing aims to diversify Indonesia's energy sources, reducing its heavy dependence on coal, which accounts for 65% of the country's energy sector. Replacing coal with local biomass, such as rice husks and forestry byproducts, reduces coal usage while utilizing renewable resources. This transition lessens environmental impact and aligns with international commitments, such as the Paris Agreement. Reducing coal use enhances resilience to global energy price fluctuations and facilitates the implementation of sustainable energy systems.

4.4.3. Improved Energy Security

The integration of biomass into the existing energy infrastructure enhances energy security by utilizing local resources. Indonesia's abundant agricultural and forestry residues, such as corn cobs and wood chips, provide a consistent supply of biomass, thereby decreasing the need for imported fuels. This strategy strengthens national

---

energy independence and creates a more reliable energy network.

4.4.4. Increased Social Benefits (Job Creation and Community Development)

The biomass supply chain provides socio-economic benefits, particularly in rural areas. Job opportunities arise throughout the supply chain, from biomass cultivation and collection to preprocessing and transportation. This job creation helps reduce poverty and boost economic development in rural areas. Additionally, switching from coal to biomass leads to improved air quality, thereby reducing health risks such as respiratory issues. Community involvement ensures fair benefit distribution and builds trust, making biomass projects socially inclusive and sustainable. These five indicators collectively answer RQ2 by providing a validated set of metrics to quantitatively assess the effectiveness of co-firing strategies simulated within the SD framework.

4.5. Potential Government Interventions in Co-Firing in Indonesia

Government interventions are critical to the successful implementation of co-firing in Indonesia. In response to RQ3's technical, economic, and social barriers, RQ4 analysis prescribes intervention:

4.5.1. Incentives for Biomass Utilization

Providing targeted financial incentives is essential to reducing the initial capital barriers for biomass co-firing. Currently, the absence of specific incentives for this technology makes it less appealing to private investors[94]. Policy interventions such as fiscal incentives, tax relief mechanisms, and guaranteed tariffs for biomass initiatives could stimulate private-sector engagement and capital inflows. Concurrently, public capital allocations toward infrastructure development, particularly thermochemical pretreatment plants, would enhance the economic viability of co-firing projects by addressing logistical bottlenecks and reducing feedstock variability costs[14].

4.5.2. Subsidy Schemes for Co-Firing Infrastructure

Investing in research and development (R&D) for advanced biomass technologies, such as torrefaction, and training programs for local stakeholders would improve the practicality of co-firing projects. Torrefied biomass offers benefits like improved boiler performance and reduced operational challenges[14]. Government-sponsored R&D programs could drive innovation and position Indonesia as a leader in biomass technology.

4.5.3. Policy Support for Biomass Supply Chain Development

Poor transportation and storage of biomass are barriers to expanding co-firing projects[94]. The government could address this by funding decentralized preprocessing facilities closer to biomass sources, reducing transport costs and energy waste. Improved logistics and supply chain management would ensure a consistent biomass supply, and the role of preprocessing technologies in enhancing cost efficiency[13].

4.5.4. Public Awareness Campaign on Co-Firing Benefits

Community support is essential for the long-term success of biomass co-firing projects. Policies that create local jobs in biomass collection, preprocessing, and transportation could foster public support [14]. Moreover, fair sharing of benefits, such as access to clean energy and reduced pollution, would increase social acceptance, especially in rural areas.

4.5.5. Carbon Pricing Policy

Cooperation among the government, private sector stakeholders, and local communities is essential for the sustainable development of biomass co-firing. Collaborative approaches, such as public-private partnerships, can facilitate the sharing of resources and expert knowledge. The government should create platforms for discussion and collaboration, especially in regions with local biomass production and use[94].

4.5.6. Biomass Pricing Policy

Indonesia needs to improve its regulations to support biomass co-firing. Unclear rules regarding biomass certification confuse investors and industry stakeholders[94]. Establishing clear guidelines and standards for biomass quality and its use in co-firing would help ensure reliability and encourage broader acceptance. These six interventions provide a direct answer to RQ4, offering targeted policy solutions designed to counteract the specific barriers identified by stakeholders (RQ3) and modulate the feedback loops (e.g., strengthening R1, mitigating B1) within the conceptual model.

To prioritize actionable steps for Indonesia's co-firing transition, Table 4 ranks the six government interventions by their potential impact (emission reduction, cost efficiency, and scalability) and implementation difficulty (fiscal/technical complexity, as well as stakeholder alignment).

This ranking, categorized into short-term (0–3 years), medium-term (3–7 years), and long-term (5–10 years), guides policymakers toward high-leverage, feasible actions for near-term decarbonization while sequencing systemic reforms for long-term net-zero goals. Criteria draw on stakeholder-validated barriers (Section 4.1) and empirical lessons from PLN pilot plants[38,70]. The rationale for the ranking is grounded in the following considerations:

- ➢ Short-term priorities target "quick wins":

Subsidies leverage PLN's existing retrofit programs[14], while incentives rapidly scale proven rice-husk co-firing (e.g., Pangkalan Susu's 42k-ton CO_2 reduction[38]).

- Medium-term policies address structural barriers: Supply chain development mitigates Barru PLTU's failure (70km transport radius)[70], while pricing policies stabilize volatile biomass markets[89].

Long-term tools require institutional maturation: Carbon pricing faces political hurdles but is critical for net-zero alignment[59], mirroring Vietnam's phased coal tax rollout[64]. This prioritization directly addresses RQ4 by translating stakeholder-identified barriers (RQ3) into a sequenced action plan, ensuring high-impact interventions like subsidy schemes are deployed first to overcome the most critical economic and technical constraints modeled in loop B1.

4.6. Stakeholders

Indonesia's stakeholders in biomass and coal co-firing include government bodies, the private sector, research institutions, local communities, and non-governmental organizations (NGOs).

4.6.1. Government Bodies

The Ministry of Energy and Mineral Resources of Indonesia plays a crucial role in developing policy frameworks, strategic roadmaps, and fiscal incentives to promote the adoption of co-firing. Aligned with national decarbonization goals, the National Energy Policy sets a target of 23% renewable energy integration by 2025 and commits to achieving net-zero emissions by 2060, positioning biomass co-firing as a transitional strategy within Indonesia's broader sustainable energy agenda[13,14]. State-owned companies like PLN are also important, as they operate coal-fired power plants and help implement co-firing plans.

4.6.2. Private Sectors

Private companies play a crucial role in supplying biomass, investing in co-firing technologies, and managing logistics. Companies focused on plantation waste, municipal waste, and biomass energy technologies are crucial to establishing a reliable biomass supply chain. Collaboration between the private and public sectors enhances the effectiveness of co-firing initiatives.

4.6.3. Research Institutions

Universities and research centers support the development of co-firing by conducting studies to improve efficiency, address technical challenges, and explore advanced methods such as torrefaction and biomass pelletization. These institutions provide scientific insights and solutions to such problems as slagging and corrosion in energy production facilities[13].

4.6.4. Local Communities

Local communities supply raw biomass materials, primarily from agricultural and forestry by-products. Their involvement in the biomass supply chain offers economic benefits, helping reduce poverty and promote rural development. Ensuring community participation and fair benefit distribution is vital for long-term support and engagement.

4.6.5. Non-Governmental Organizations (NGOs)

NGOs promote sustainable energy practices and monitor co-firing initiatives to ensure they meet environmental and social objectives. They work with government and local stakeholders to advance policies aligned with global ecological commitments and regional sustainability goals[14].

This study presents several recommendations to enhance the effectiveness of co-firing implementation. Strengthening policy is crucial for establishing clear regulatory frameworks and standards for biomass certification and utilization, attracting investment, and aligning with global climate objectives. Financial incentives, such as subsidies, tax exemptions, and other support mechanisms, can reduce initial costs and facilitate infrastructure development. Infrastructure investment is necessary to build local preprocessing plants, lower biomass transport costs, and improve supply chain efficiency. Strengthening collaborative frameworks between public and private institutions can enhance the

Table 4: Ranking of Government Interventions by Impact vs. Implementation Difficulty

Intervention	Potential Impact	Implementation Difficulty	Priority Level	Timeline
Subsidy schemes for co-firing infrastructure	High (↑ efficiency, ↓ slagging)	Low (builds on PLN retrofitting)	1. Short-term	0–2 years
Incentives for biomass utilization	High (↑ adoption)	Medium (requires fiscal space)	2. Short-term	0–3 years
Policy support for supply chain development	High (↓ logistics costs)	High (cross-agency coordination)	3. Medium-term	2–5 years
Biomass pricing policy	Medium (market stability)	Medium (regulatory design)	4. Medium-term	3–7 years
Carbon pricing policy	High (↑ emission cuts)	High (political resistance)	5. Long-term	5–10 years
Public awareness campaigns	Medium (↑ acceptance)	Low (NGO partnerships)	6. Continuous	Ongoing

pooling of resources and the dissemination of expertise, thereby supporting the implementation of large-scale initiatives through shared technological and operational efforts. Local engagement should prioritize job creation and equitable benefit-sharing to foster community support and promote social equity. Research and capacity-building efforts should focus on investing in advanced biomass technologies and training programs to improve technical efficiency and sustainability. Finally, ongoing sustainability monitoring through continuous emissions tracking will ensure compliance with environmental standards and contribute to long-term climate goals.

4.7. Roadmap for Operationalizing Conceptual Model for Evaluating Biomass and Coal Co-firing in Indonesia

To bridge the gap between theoretical modeling and on-ground implementation, this study embeds the System Dynamics (SD) conceptual framework within a five-phase operational roadmap for biomass-coal co-firing in Indonesia, as shown in Table 2. This structured pathway—spanning Model Structuring, Data Collection, Model Calibration, Scenario Testing, and Stakeholder Integration—translates causal relationships (e.g., loops R1–R4, B1) and output indicators (CO_2 reduction, social benefits) into targeted strategies for decarbonizing Indonesia’s coal-dependent energy sector.

By embedding Indonesia-specific causal relationships (e.g., loops R1-R4, B1) and output indicators, this roadmap extends beyond theoretical modeling by institutionalizing feedback between SD outputs tailored to the Indonesian context and national policy. For instance, emission reduction trajectories from scenario testing directly inform Indonesia’s renewable targets, while stakeholder compliance metrics (e.g., job creation/tons biomass) enable adaptive governance. As a replicable template for Global South energy transitions, it demonstrates how system dynamics can scalably convert sustainability frameworks into investable actions.

4.8. Scientific Contribution, Implications, and Limitations

4.8.1. Scientific Contribution

The primary scientific contribution of this research is the development of an integrated, Indonesia-centric SD framework that moves beyond static analyses. While previous studies have applied SD to energy transitions in other regions[20,21,64]This is the first model to explicitly incorporate variables such as spatially fragmented feedstock supply chains, regionally divergent retrofit costs, and policy implementation delays, thereby modeling the co-firing ecosystem in Indonesia. The framework's novelty lies in its ability to quantify the reinforcing loops (e.g., policy-driven cost efficiency) and balancing loops (e.g., supply chain constraints) that determine the viability of co-firing across different islands.

By translating theoretical co-firing potential into a simulation-ready conceptual model, this study addresses a critical gap between national decarbonization ambitions and implementable pathways. It provides a methodological foundation for future quantitative SD simulations to test biomass blend scenarios across Indonesia's 52 power plants, offering a scalable tool for other archipelagic nations in the Global South facing similar energy transition complexities.

4.8.2. Practical Implications of Prioritised Interventions

The prioritization of government interventions (Table 4) translates the model's dynamics into an actionable policy sequence. The ranking reflects a strategic understanding of the feedback loops: near-term interventions target the most potent leverage points within the system.

Short-term interventions (Subsidy schemes, Incentives) are designed to directly amplify reinforcing loop R1 (Policy-Driven Cost Efficiency) and mitigate balancing loop B1 (Technical/Supply Chain Constraints). By leveraging existing PLN retrofit programs and scaling proven co-firing models, these policies can generate rapid emission reductions and build momentum, as evidenced by the success of the Paiton and Pangkalan Susu plants.

Medium-term policies (Supply chain development, Biomass pricing) address the structural barriers embedded in B1, such as the high logistics costs that doomed the Barru pilot. Establishing decentralized preprocessing hubs is a direct response to the archipelagic challenge of supply chain fragmentation.

Long-term tools (Carbon pricing) aim to strengthen R4 (Emission Reduction) by aligning economic incentives with decarbonization goals, though their implementation requires significant political will and institutional capacity building.

This phased approach enables policymakers to achieve quick wins while systematically addressing deeper, systemic barriers, thereby optimizing resource allocation and enhancing the likelihood of attaining Indonesia's net-zero target by 2060.

4.8.3. Limitations

While the study advances co-firing research, several limitations warrant consideration. First, the qualitative SD phase, which relies on stakeholder perceptions for causal loop mapping, lacks empirical validation through quantitative simulation. The model's variables and relationships, although validated by experts, require testing with real-world data. Second, regional implementation gaps are underaddressed; Java-centric data may not fully capture the logistical constraints or variable biomass types (e.g., rice husks vs. municipal waste) in Eastern Indonesia.

The model also excludes critical dynamics such as competition between biomass and food production, global coal price volatility, and climate impacts on feedstock yields. Furthermore, data constraints—such as incomplete power plant records from PLN—risk oversimplifying technical variables like retrofit costs. Finally, the operational roadmap assumes a linear policy rollout, potentially overlooking bureaucratic delays or funding shortfalls that are common in complex energy transitions. Future research should address these limitations through quantitative modeling and more granular regional analysis.

5. Conclusion

This study established Indonesia's first stakeholder-validated System Dynamics framework for evaluating biomass-coal co-firing, providing a holistic tool to navigate the complex, non-linear interdependencies of the nation's archipelagic energy transition. The primary achievement is the identification and mapping of critical feedback mechanisms, most notably the balancing loop B1 (Technical/Supply Chain Constraints), which reveals how feedstock variability and logistical bottlenecks fundamentally cap biomass adoption rates and pose the most significant barrier to scaling co-firing initiatives. This finding underscores that without targeted intervention, these inherent constraints will persistently hinder progress. Consequently, the highest-priority policy recommendation emerging from this analysis is the immediate implementation of subsidy schemes for co-firing infrastructure, particularly for decentralized torrefaction and preprocessing facilities. This intervention directly counteracts the B1 loop by mitigating retrofit costs and stabilizing supply chains, offering the most effective lever for near-term decarbonization gains.

To build upon this conceptual foundation, future research must transition to quantitative simulation to test and refine these dynamics. The most critical next step is the development of a quantitative SD model, parameterized with operational data from Indonesia's 52 co-firing plants, which will enable the testing of biomass blend scenarios and policy impacts under region-specific conditions. Further research should also focus on spatial land-use conflict analysis to resolve food-energy competition in biomass sourcing, as well as stochastic modeling to incorporate risks from climate disruptions and global market volatility. By advancing in these specific directions, this framework can evolve from a conceptual map into a robust decision-support tool, directly accelerating Indonesia's pathway to net-zero emissions.

Acknowledgment

The Authors express gratitude to the National Research and Innovation Agency (BRIN) for providing essential funding for this research.

References

1) Badan Pusat Statistik (BPS), "Energy Balances of Indonesia 2019-2023", BPS-Statistics Indonesia, Jakarta, Indonesia (2024).
2) A. H. Kuncoro, J. Santosa, I. Fitriana, A. Nurrohim, A. Sugiyono, E. Djubaedah, V. Nurliyanti, N. Niode, and P. T. Wijaya, "Towards net zero emission in Indonesia: A strategic fuel demand analysis for sustainable electricity (2022-2060)," Evergreen, Vol. 11, pp. 3606-3617, (2024). doi:10.5109/7326993.
3) Ministry of Energy and Mineral Resources (ESDM) Republic of Indonesia, "Regulation on the Implementation of Energy and Mineral Resources Sector," Ministerial Regulation No. 2021 (2021).
4) L. Abdulah, S. Astana, S. F. Purba, Subarudi, Darwo, M. A. Qirom, S. Andini, Y. Rochmayanto, M. Wardani, D. Yuniati, Y. Indrajaya, I. W. W. Susila, D. Djaenudin, I. Gunawan, R. Effendi, and Hariyadi, "An integrated spatial-dynamic model for sustainable biomass supply to coal-fired power plants," Trees Forests People, vol. 20, p. 100903 (2025). doi:10.1016/j.tfp.2025.100903.
5) A. Hidayatno, A.R. Destyanto, and M. Fadhil, “Model conceptualization on e-commerce growth impact to emissions generated from urban logistics transportation: a case study of jakarta,” Energy Procedia, 156 (September 2018) 144–148 (2019). doi:10.1016/j.egypro.2018.11.119.
6) N. A. Sasongko, M. L. D. Wardani, N. G. Putra, E. Hilmawan, G. A. Pertiwi, N. S. Laili, N. Ariyanto, T. Handayani, M. Anda, and D. Goodfield, "Biomass co-firing in coal power plants: Analyzing combustion characteristics and emission reductions" Evergreen, vol. 11, no. 4, pp. 3576–3594 (2024). doi:10.5109/7326991.
7) M. P. Helios, A. Andini, A. P. Nuryadi, A. Maswan, H. Sutriyanto, H. Pujowidodo, B. T. Prasetyo, A. D. Nugraha, and N. Cahyo, "Numerical modelling of co-firing combustion in an existing coal-fired power plant: A case study in Paiton 9," Evergreen, vol. 11, pp. 2638-2649 (2024). doi:10.5109/7236903.
8) T. Hidayat, D. Budianto, D. Kurniawati, Y. Ahda, I. Arnif, S. Nur Endah Eny, W. Chaeruni, and R. Ardiana, “Investigation of loop seal pressure in circulating fluidized bed: a comparative analysis of biomass combustion,” Evergreen, vol. 11, pp. 2755-2760 (2024). doi:10.5109/7236914.
9) B.N. Madanayake, S. Gan, C. Eastwick, and H.K. Ng, “Biomass as an energy source in coal co-firing and its feasibility enhancement via pre-treatment techniques,” Fuel Processing Technology, 159 287–305 (2017). doi:10.1016/j.fuproc.2017.01.029.
10) A. Dwijatmiko, A. Nurrohim, J. Santosa, A. Sugiyono, A.H. Kuncoro, I. Rahardjo, A. Subandriya,

and E. Siregar, “Optimizing electricity supply for jawa-madura-bali: scenarios for achieving net zero emissions,” Evergreen, 11 (3) 2567–2579 (2024). doi:10.5109/7236897.

11) J. Singh, P. Srivastava, and D. Goyal, "Study of biomass torrefaction fundamentals and properties," Evergreen, vol. 10, no. 1, pp. 348–355 (2024). doi:10.5109/6781092.

12) PT. PLN (Persero), "Having Great Potential, PLN Develops Biomass Based on Community Involvement," Press Release, Jakarta, Indonesia (Sep. 22, 2023).

13) A.D. Pasek, M. Soleh, F.B. Juangsa, and P.S. Darmanto, “Progress on biomass coal co-firing for indonesia power plant,” IOP Conf Ser Earth Environ Sci, 1395 (1) (2024). doi:10.1088/1755-1315/1395/1/012009.

14) G. N. P. Tampubolon and B. A. Dwiyantoro, "Study on the effect of co-firing ratio of coal and torrefied biomass fuel on boiler performance," J. Tek. Mesin Indones., vol. 12, no. 3, pp. 3–8 (2023).

15) K. Miyamoto, S.N. Pratiwi, S. Nishiiri, H. Takaguchi, and T. Kubota, “Relationship between cooling methods and energy consumption for the development of low-carbon collective housing in indonesia,” Sustainability (Switzerland), 16 (4) (2024). doi:10.3390/su16041635.

16) H.K. Bokka, and H.C. Lau, “Decarbonizing borneo’s power and industry sectors by carbon capture and storage,” Geoenergy Science and Engineering, 226 (2023). doi:10.1016/j.geoen.2023.211796.

17) M. Tjahjono, I. Stevani, G.A. Siswanto, A. Adhitya, and I. Halim, “Assessing the feasibility of gray, blue, and green ammonia productions in indonesia: a techno-economic and environmental perspective,” International Journal of Renewable Energy Development, 12 (6) 1030–1040 (2023). doi:10.14710/ijred.2023.58035.

18) Z. Arifin, V.F.S. Insani, M. Idris, K.R. Hadiyati, Z. Anugia, and D. Irianto, “Techno-economic analysis of co-firing for pulverized coal boilers power plant in Indonesia,” International Journal of Renewable Energy Development, 12 (2) 261–269 (2023). doi:10.14710/ijred.2023.48102.

19) B. Morrison and J. S. Golden, "Life cycle assessment of co-firing coal and wood pellets in the southeastern United States," J. Clean. Prod., vol. 150, pp. 188–196 (2017). Doi:10.1016/j.jclepro.2017.03.026.

20) H. Zhao, B. Li, X. Wang, H. Lu, and H. Li, "Evaluating the performance of China’s coal-fired power plants considering the coal depletion cost: A system dynamic analysis," J. Clean. Prod., vol. 275, p. 122809 (2020). doi:10.1016/j.jclepro.2020.122809.

21) J. Chen, T.H.-K. Yu, S.-Y. Chou, and T.-A.-T. Nguyen, “Simulating the effects of offshore wind energy policy on decarbonization and industrial growth in taiwan: a system dynamics approach,” Energy for Sustainable Development, 71 490–504 (2022). doi:10.1016/j.esd.2022.10.018.

22) G. K. Parshetti, A. Quek, R. Betha, and R. Balasubramanian, "TGA–FTIR investigation of co-combustion characteristics of blends of hydrothermally carbonized oil palm biomass (EFB) and coal," Fuel processing technology, vol. 118, pp. 228-234 (2014). doi:10.1016/j.fuproc.2013.09.010.

23) Y. Wahyono, N. A. Sasongko, D. A. Trench, M. A. E, G. Hadiyanto, H. N. Aisyah, and I. D. Ariyanti, "Assessing the impact of climate change and water scarcity on ferronickel production in Indonesia: A life cycle assessment approach," Sustainable Energy Technologies and Assessments, vol. 67, p. 103835 (2024). doi:10.1016/j.seta.2024.103835.

24) M. Sajdak, M. Kmieć, B. Micek, and J. Hrabak, "Determination of the optimal ratio of coal to biomass in the co-firing process: Feed mixture properties," Int. J. Environ. Sci. Technol., vol. 16, pp. 2989-3000 (2019). doi:10.1007/s13762-018-1864-y.

25) N. K. Supriatna, A. Kismanto, I. Purawiardi, R. Alamsyah, N. W. Hesty, P. Zuldian, O. Fariza, A. A. Raksodewanto, and A. Surjosatyo, "Economic feasibility study of syngas-derived garden waste biomass as liquified petroleum gas substitute in Indonesia: A case study for 1-megawatt updraft fixed bed gasifier," Evergreen, vol. 10, p. 1835-1846 (2023). doi:10.5109/7151733.

26) D. Magalhaes, and F. Kazanc, “Influence of biomass thermal pre-treatment on the particulate matter formation during pulverized co-combustion with lignite coal,” Fuel, 308 (2022). doi:10.1016/j.fuel.2021.122027.

27) L. Mu, T. Li, Z. Wang, Y. Shang, and H. Yin, “Influence of water/acid washing pretreatment of aquatic biomass on ash transformation and slagging behavior during co-firing with bituminous coal,” Energy, 234 (2021). doi:10.1016/j.energy.2021.121286.

28) R. K. Ahmad, S. A. Sulaiman, M. A. B. A. Majid, S. Yusuf, S. S. Dol, M. Inayat, and H. A. Umar, "Assessing the technical and environmental potential of coconut shell biomass: Experimental study through pyrolysis and gasification," Evergreen, vol. 10, pp. 585-593 (2023). doi:10.5109/6782165.

29) J. L. G. Juan, K. B. Aviso, R. R. Tan, and C. L. Sy, "A multi-objective optimization model for the design of biomass co-firing networks integrating feedstock quality considerations," Energies, vol. 12, pp. 2252 (2019). doi:10.3390/en12122252.

30) M. S. Roni, S. Chowdhury, S. Mamun, M. Marufuzzaman, W. Lein, and S. Johnson, "Biomass co-firing technology with policies, challenges, and

opportunities: A global review," Renew. Sustain. Energy Rev., vol. 78, pp. 1089–1101 (2017). doi:10.1016/j.rser.2017.05.023.

31) S.G. Sahu, N. Chakraborty, and P. Sarkar, "Coal-biomass co-combustion: an overview," Renewable and Sustainable Energy Reviews, 39 575–586 (2014). doi:10.1016/j.rser.2014.07.106.

32) Y. C. Dwiaji, "Analysis of the effect of biomass co-firing on the performance of boiler equipment at coal power plant unit 1 PT. XYZ," J. Appl. Mech. Eng. Renew. Energy, vol. 3, no. 1, pp. 7–15 (2023). Doi:10.52158/jamere.v3i1.445.

33) N. Hodžić, I. Smajević, and A. Kazagić, "Concept of co-firing coal with biomass and natural gas - on track of sustainable solution for future thermal power plants," Thermal Science, 20 (4) 1171–1184 (2016). doi:10.2298/TSCI151126078H.

34) Y. C. Dwiaji, "Analysis of the effect of biomass co-firing on the performance of boiler equipment at coal power plant unit 1 PT. XYZ," J. Appl. Mech. Eng. Renew. Energy, vol. 3, no. 1, pp. 7–15 (2023). doi:10.52158/jamere.v3i1.445.

35) S. Soltani, H. Athari, M. Rosen, S. M. S. Mahmoudi, and T. Morosuk, "Thermodynamic analyses of biomass post-firing and co-firing combined cycles," World Sustain. Forum 2014, p. 1-14 (2014). doi:10.3390/wsf-4-e019.

36) S. Ahmed, M. A. Rashid, S. B. Yaakob, A. Yusof and N. C. Saha, "Performance analysis and study of economic feasibility of biomass coal co-fired power system," 2014 IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014), Langkawi, Malaysia, 2014, pp. 68-72, doi: 10.1109/PEOCO.2014.6814401.

37) Z. Arifin, V.F.S. Insani, M. Idris, K.R. Hadiyati, Z. Anugia, and D. Irianto, "Techno-economic analysis of co-firing for pulverized coal boilers power plant in indonesia," International Journal of Renewable Energy Development, 12 (2) 261–269 (2023). doi:10.14710/ijred.2023.48102.

38) Hariana, Prabowo, E. Hilmawan, F. Milky Kuswa, A. Darmawan, and M. Aziz, "A comprehensive evaluation of cofiring biomass with coal and slagging-fouling tendency in pulverized coal-fired boilers," Ain Shams Engineering Journal, 14 (7) 102001 (2023). doi:10.1016/j.asej.2022.102001.

39) J. Li, R. Wang, H. Li, Y. Nie, X. Song, M. Li, M. Shi, X. Zheng, W. Cai, and C. Wang, "Unit-level cost-benefit analysis for coal power plants retrofitted with biomass co-firing at a national level by combined gis and life cycle assessment," Appl Energy, 285 (October 2020) 116494 (2021). doi:10.1016/j.apenergy.2021.116494.

40) S. Ahmed, M. A. Rashid, S. B. Yaakob, A. Yusof and N. C. Saha, "Performance analysis and study of economic feasibility of biomass coal co fired power system," 2014 IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014), Langkawi, Malaysia, 2014, pp. 68-72, doi: 10.1109/PEOCO.2014.6814401.

41) M. F. Praevia and W. Widayat, "Analysis of the utilization of empty palm oil fruit bunches as co-firing in coal-fired power plants," J. Energi Baru Terbarukan, vol. 3, no. 1, pp. 28–37 (2022). doi:10.14710/jebt.2022.13367.

42) O. Wyman, World Energy Trilemma: 2013 Energy Sustainability Index, World Energy Council, London, UK (2013).

43) S. Knapp, A. Güldemund, S. Weyand, and L. Schebek, "Evaluation of co-firing as a cost-effective short-term sustainable co2 mitigation strategy in germany," Energy Sustain Soc, 9 (1) (2019). doi:10.1186/s13705-019-0214-3.

44) Y.W. Pratama, W.W. Purwanto, T. Tezuka, B.C. McLellan, D. Hartono, A. Hidayatno, and Y. Daud, "Multi-objective optimization of a multiregional electricity system in an archipelagic state: the role of renewable energy in energy system sustainability," Renewable and Sustainable Energy Reviews, 77 (April 2017) 423–439 (2017). doi:10.1016/j.rser.2017.04.021.

45) Z. Zanjani, I. Soares, and P. Macedo, "The nexus between CO2 emissions from electricity generation, GDP and energy intensity using a complete maximum entropy approach: The case of Iran," Energy Rep., vol. 8, pp. 319–324 (2022). doi:10.1016/j.egyr.2022.01.058.

46) K. Joensuu, and T. Sinkko, "Harvesting straw in poland and finland: how does it affect greenhouse gas emissions, biodiversity and soil physical quality?," International Journal of Energy Sector Management, 12 (1) 67–78 (2018). doi:10.1108/IJESM-01-2017-0007.

47) K. B. Aviso, C. L. Sy, R. R. Tan, and A. T. Ubando, "Fuzzy optimization of carbon management networks based on direct and indirect biomass co-firing," Renew. Sustain. Energy Rev., vol. 132, p. 110035 (2020). doi:10.1016/j.rser.2020.110035.

48) S. Xie, Q. Yang, Q. Wang, H. Zhou, P. Bartocci, and F. Fantozzi, "Coal power decarbonization via biomass co-firing with carbon capture and storage: Tradeoff between exergy loss and GHG reduction," Energy Convers. Manag., vol. 288, p. 117155 (2023). doi:10.1016/j.enconman.2023.117155.

49) W. Wang, "Integrated assessment of economic supply and environmental effects of biomass co-firing in coal power plants: a case study of jiangsu, china," Energies (Basel), 16 (6) (2023). doi:10.3390/en16062725.

50) R. Azargohar, A. Dalai, E. Hassanpour, and S. Moshiri, “Agri-pellets as alternative fuels for coal-fired power plants in canada,” International Journal of Energy Sector Management, 16 (5) 876–898 (2022). doi:10.1108/IJESM-06-2021-0005.

51) C. C. Kung, B. McCarl, X. Cao, and H. Xie, "Bioenergy prospects in Taiwan using set-aside land - an economic evaluation," China Agric. Econ. Rev., vol. 5, no. 4, pp. 489–511 (2013). doi:10.1108/CAER-01-2012-0002.

52) K. Joensuu, and T. Sinkko, “Harvesting straw in Poland and Finland,” International Journal of Energy Sector Management, 12 (1) 67–78 (2018). doi:10.1108/IJESM-01-2017-0007.

53) B. Kong, and K.P. Gallagher, “The new coal champion of the world: the political economy of chinese overseas development finance for coal-fired power plants,” Energy Policy, 155 (May) 112334 (2021). doi:10.1016/j.enpol.2021.112334.

54) E. Rokni, X. Ren, A. Panahi, and Y.A. Levendis, “Emissions of so2, nox, co2, and hcl from co-firing of coals with raw and torrefied biomass fuels,” Fuel, 211 (September 2017) 363–374 (2018). doi:10.1016/j.fuel.2017.09.049.

55) S. Fatima and M. Zeeshan, "Energy potential assessment and geospatial site suitability analysis for crop residue-based power plants in Pakistan," Sustain. Prod. Consum., vol. 45, pp. 488–508 (2024). Doi:10.1016/j.spc.2024.01.023.

56) S. Nepal and L. T. Tran, "Identifying trade-offs between socio-economic and environmental factors for bioenergy crop production: A case study from northern Kentucky," Renew. Energy, vol. 142, pp. 272–283 (2019). doi:10.1016/j.renene.2019.04.110.

57) E. J. Ordonez-Frías, J. A. Azamar-Barrios, E. Mata-Zayas, O. Silvan-Hernandez, and L. Pampillon-Gonzalez, "Bioenergy potential and technical feasibility assessment of residues from oil palm processing: A case study of Jalapa, Tabasco, Mexico," Biomass Bioenergy, vol. 142, p. 105668 (2020). doi:10.1016/j.biombioe.2020.105668.

58) K. Pactwa, J. Wozniak, and M. Dudek, "Coal mining waste in Poland in reference to circular economy principles," Fuel, vol. 270, p. 117493 (2020). doi:10.1016/j.fuel.2020.117493.

59) C. V. Squire, J. Lou, and T.C. Hilde, “The viability of co-firing biomass waste to mitigate coal plant emissions in indonesia,” Commun Earth Environ, 5 (1) 1–14 (2024). doi:10.1038/s43247-024-01588-0.

60) S. Selvakkumaran, and E.O. Ahlgren, “Review of the use of system dynamics (sd) in scrutinizing local energy transitions,” J Environ Manage, 272 111053 (2020). doi:10.1016/j.jenvman.2020.111053.

61) S. Lawrence, D.R. Herber, and K.E. Shahroudi, “Leveraging system dynamics to predict the commercialization success of emerging energy technologies: lessons from wind energy,” Energies (Basel), 18 (8) 2048 (2025). doi:10.3390/en18082048.

62) G. Tu, and Z. Zan, “The green paradox of new energy vehicles: a system dynamics analysis,” Sustainability, 17 (9) 3938 (2025). doi:10.3390/su17093938.

63) R. Zhang, X. Ai, and H. Li, "How to design subsidy policies for clean energy projects? A study on ‘coal-to-gas’ project in China," Resour. Policy, vol. 85, p. 103928 (2023). doi:10.1016/j.resourpol.2023.103928.

64) A. H. Truong, M. Ha-Duong, and H. A. Tran, "Economics of co-firing rice straw in coal power plants in Vietnam," Renew. Sustain. Energy Rev., vol. 154, p. 111742 (2022). doi:10.1016/j.rser.2021.111742.

65) B. Yang, Y.-M. Wei, Y. Hou, H. Li, and P. Wang, "Life cycle environmental impact assessment of fuel mix-based biomass co-firing plants with CO2 capture and storage," Appl. Energy, vol. 252, p. 113483 (2019). doi:10.1016/j.apenergy.2019.113483.

66) S. Sammarchi, J. Li, D. Izikowitz, Q. Yang, and D. Xu, "China’s coal power decarbonization via CO2 capture and storage and biomass co-firing: A LCA case study in Inner Mongolia," Energy, vol. 261, p. 125158 (2022). doi:10.1016/j.energy.2022.125158.

67) Y. Liu and Y. Shen, "Modelling and optimisation of biomass injection in ironmaking blast furnaces," Prog. Energy Combust. Sci., vol. 87, p. 100952 (2021). doi:10.1016/j.pecs.2021.100952.

68) X. Chen, and X. Wu, “The roles of carbon capture, utilization and storage in the transition to a low-carbon energy system using a stochastic optimal scheduling approach,” J Clean Prod, 366 (2022). doi:10.1016/j.jclepro.2022.132860.

69) X. Chen and X. Wu, "The roles of carbon capture, utilization and storage in the transition to a low-carbon energy system using a stochastic optimal scheduling approach," J. Clean. Prod., vol. 366, p. 132860 (2022). doi:10.1016/j.jclepro.2022.132860.

70) PLN Energi Primer Indonesia (PLN EPI), "Biomass," Company Website, Accessed: Jan. 2024.

71) S.E. Ibitoye, R.M. Mahamood, T.-C. Jen, C. Loha, and E.T. Akinlabi, “An overview of biomass solid fuels: biomass sources, processing methods, and morphological and microstructural properties,” Journal of Bioresources and Bioproducts, 8 (4) 333–360 (2023). doi:10.1016/j.jobab.2023.09.005.

72) N. A. Sasongko, N. G. Putra, and M. L. D. Wardani, "Review of types of biomass as a fuel-combustion feedstock and their characteristics," Adv. Food Sci. Sustain. Agric. Agroind. Eng., vol. 6, no. 2, pp. 170–184 (2023). doi:10.21776/ub.afssaae.2023.006.02.8.

73) P.A. Nuramalia, S.A. Amanda, M.P. Helios, E.W.

Tjahjono, E. Ferdy Destian, E.R. Finalis, B.A. Firmandoko, H. Sutriyanto, M. Saleh, and H. Bangun, “Biomass fuel quality improvement using hydrogen peroxide and demineralized water pre-treatment and torrefaction,” Evergreen, vol. 10, pp.2949-2958 (2024). doi:10.5109/7326936.

74) F. Sher, A. Yaqoob, F. Saeed, S. Zhang, Z. Jahan, and J. J. Klemeš, "Torrefied biomass fuels as a renewable alternative to coal in co-firing for power generation," Energy, vol. 209, p. 118444 (2020). doi:10.1016/j.energy.2020.118444.

75) M. Tymoszuk, J. Wnorowska, and S. Kalisz, “Grindability features of torrefied biomass,” Energies (Basel), 18 (7) 1824 (2025). doi:10.3390/en18071824.

76) F. Sher, A. Yaqoob, F. Saeed, S. Zhang, Z. Jahan, and J.J. Klemeš, “Torrefied biomass fuels as a renewable alternative to coal in co-firing for power generation,” Energy, 209 118444 (2020). doi:10.1016/j.energy.2020.118444.

77) W.-H. Chen, B.-J. Lin, Y.-Y. Lin, Y.-S. Chu, A.T. Ubando, P.L. Show, H.C. Ong, J.-S. Chang, S.-H. Ho, A.B. Culaba, A. Pétrissans, and M. Pétrissans, “Progress in biomass torrefaction: principles, applications and challenges,” Prog Energy Combust Sci, 82 100887 (2021). doi:10.1016/j.pecs.2020.100887.

78) D. Maxwell, B.A. Gudka, J.M. Jones, and A. Williams, “Emissions from the combustion of torrefied and raw biomass fuels in a domestic heating stove,” Fuel Processing Technology, 199 106266 (2020). doi:10.1016/j.fuproc.2019.106266.

79) Nurkamelia, Sugihardjo, B. Widarsono, Usman, Suliantara, S. Kepies, D. Dwiyanarti, D. Sunarjanto, M. Romli, and T.M. Susantoro, “Potential of ccs in east kalimantan’s coal-power sector for achieving net-zero emissions,” Evergreen, 11 (3) 2555–2566 (2024). doi:10.5109/7236896.

80) L. Cutz, G. Berndes, and F. Johnsson, “A techno-economic assessment of biomass co-firing in czech republic, france, germany and poland,” Biofuels, Bioproducts and Biorefining, 13 (5) 1289–1305 (2019). doi:10.1002/bbb.2034.

81) B. Yang, Y.M. Wei, L.C. Liu, Y.B. Hou, K. Zhang, L. Yang, and Y. Feng, “Life cycle cost assessment of biomass co-firing power plants with co2 capture and storage considering multiple incentives,” Energy Econ, 96 105173 (2021). doi:10.1016/j.eneco.2021.105173.

82) T. Furubayashi, and T. Nakata, “Cost and co2 reduction of biomass co-firing using waste wood biomass in tohoku region, japan,” J Clean Prod, 174 1044–1053 (2018). doi:10.1016/j.jclepro.2017.11.041.

83) J.-X. Guo, “Retrofitting strategy for biomass co-fired power plant,” Clean Technol Environ Policy, 24 (8) 2531–2545 (2022). doi:10.1007/s10098-022-02332-y.

84) A. Paletto, S. Bernardi, E. Pieratti, F. Teston, and M. Romagnoli, “Assessment of environmental impact of biomass power plants to increase the social acceptance of renewable energy technologies,” Heliyon, 5 (7) e02070 (2019). doi:10.1016/j.heliyon.2019.e02070.

85) P. Chowdhury, N. A. Mahi, R. Yeassin, N.-U.-R. Chowdhury, and O. Farrok, "Biomass to biofuel: Impacts and mitigation of environmental, health, and socioeconomic challenges," Energy Convers. Manage. X, vol. 25, p. 100889 (2025). doi:10.1016/j.ecmx.2025.100889.

86) T. Herawati, D. Rohadi, M. Rahmat, and B. Winarno, "An exploration of gender equity in household: A case from a peatland-based community in Riau, Indonesia," Biodiversitas, vol. 20, no. 3, pp. 853–861 (2019). Doi:10.13057/biodiv/d200332.

87) Z. M. Tun, M. Christwardana, R. Adiguna, H. Hadiyanto, and J. Windarta, "A mini review on the biomass energy implementation from economic perspective in Indonesia," J. Bioresour. Environ. Sci., vol. 2, no. 1, pp. 101–108 (2023). doi:10.14710/jbes.2023.17067.

88) M. Zhai, X. Tian, Z. Liu, Y. Zhao, Y. Deng, and W. Yang, "Advancing just transition: The role of biomass co-firing in emission reductions and employment for coal regions," Sustain. Energy Technol. Assess., vol. 75, p. 104246 (2025). doi:10.1016/j.seta.2025.104246.

89) U. Abdela, "Review on environmental and social impacts of rural household traditional biomass energy utilization," J. Energy Technol. Policy, vol. 9, no. 9, pp. 1–13 (2019). doi:10.7176/jetp/9-9-01.

90) R. Budiarto, D. Novitasari, A. R. Izzati, and W. P. Sari, "Unraveling the sustainability footprint: A descriptive analysis of co-firing technologies for advancing energy transition in Indonesia," J. Phys. Conf. Ser., vol. 2828, no. 1, p. 012040 (2024). doi:10.1088/1742-6596/2828/1/012040.

91) L. Liu, M. Z. Memon, Y. Xie, S. Gao, Y. Guo, J. Dong, Y. Gao, A. Li, and G. Ji, "Recent advances of research in coal and biomass co-firing for electricity and heat generation," Circ. Econ., vol. 2, no. 4, p. 100063 (2023). doi:10.1016/j.cec.2023.100063.

92) Y. Xu, K. Yang, J. Zhou, and G. Zhao, “Coal-biomass co-firing power generation technology: current status, challenges and policy implications,” Sustainability, 12 (9) 3692 (2020). doi:10.3390/su12093692.

93) R.R. Kommalapati, I. Hossan, V.S.V. Botlaguduru, H. Du, and Z. Huque, “Life cycle environmental impact of biomass co-firing with coal at a power plant

in the greater houston area," Sustainability (Switzerland), 10 (7) (2018). doi:10.3390/su10072193.

94) C. Yosiana and I. G. A. K. R. Handayani, "Harmonizing biomass co-firing with the green economy paradigm: A sustainable approach for Indonesia's energy landscape," Int. J. Relig., vol. 5, no. 9, pp. 170–184 (2024). doi:10.61707/fz77fc17.

95) Y. Xu, K. Yang, J. Zhou, and G. Zhao, "Coal-biomass co-firing power generation technology: current status, challenges and policy implications," Sustainability (Switzerland), 12 (9) (2020). doi:10.3390/su12093692.

96) S.J. Sofán-Germán, M.E. Doria-Oviedo, J.D. Rhenals-Julio, and J.M. Mendoza-Fandiño, "Life cycle assessment of biomass waste and coal co-firing: advancing circular economy in energy production," Recycling, 10 (4) 151 (2025). doi:10.3390/recycling10040151.

97) C. Liu, H. Chen, R. Xu, and Y. Wang, "Minimizing the resource consumption of heterogeneous batch-processing machines using a copula-based estimation of distribution algorithm," Appl. Soft Comput., vol. 73, pp. 283–305 (2018). doi:10.1016/j.asoc.2018.08.036.

98) J. Zhang, G. Sun, J. Liu, F. Evrendilek, and M. Buyukada, "Co-combustion of textile dyeing sludge with cattle manure: Assessment of thermal behavior, gaseous products, and ash characteristics," J. Clean. Prod., vol. 253, p. 119950 (2020). doi:10.1016/j.jclepro.2019.119950.

99) V. Kazulis, H. Vigants, I. Veidenbergs, and D. Blumberga, "Biomass and natural gas co-firing - evaluation of ghg emissions," Energy Procedia, 147 558–565 (2018). doi:10.1016/j.egypro.2018.07.071.

100) M.N. Mohd Idris, H. Hashim, and N.H. Razak, "Spatial optimisation of oil palm biomass co-firing for emissions reduction in coal-fired power plant," J Clean Prod, 172 3428–3447 (2018). doi:10.1016/j.jclepro.2017.11.027.

101) J. Han, D. Yu, J. Wu, X. Yu, F. Liu, and M. Xu, "Effects of torrefaction on ash-related issues during biomass combustion and co-combustion with coal. part 3: ash slagging behavior," Fuel, 339 126925 (2023). doi:10.1016/j.fuel.2022.126925.

102) A. Tu, Z. Zhang, and Z. Gao, "Review on carbon capture technology of oxy-fuel combustion in coal fired boiler," IOP Conf. Ser. Earth Environ. Sci., vol. 827, no. 1, p. 012012 (2021). doi:10.1088/1755-1315/827/1/012012.

103) S. Talei, D. Fozer, P. S. Varbanov, A. Szanyi, and P. Mizsey, "Oxyfuel combustion makes carbon capture more efficient," ACS Omega, vol. 9, pp. 3250–3261 (2024). doi:10.1021/acsomega.3c05034.

104) C. V. Squire, J. Lou, and T.C. Hilde, "The viability of co-firing biomass waste to mitigate coal plant emissions in indonesia," Commun Earth Environ, 5 (1) 423 (2024). doi:10.1038/s43247-024-01588-0.

105) K. Hasan and A. B. Swastika, "Biomass Co-firing in Indonesia: Prolonging, Not Solving Coal Problem," Institute for Essential Services Reform (IESR) Report, Jakarta, Indonesia (2025).

106) M.A. Rahmanta, A. Aprilana, Ruly, N. Cahyo, T.W.D. Hapsari, and E. Supriyanto, "Techno-economic and environmental impact of biomass co-firing with carbon capture and storage in indonesian power plants," Sustainability, 16 (8) 3423 (2024). doi:10.3390/su16083423.

107) P. Adhiguna, "Indonesia's Biomass Cofiring Bet," Institute for Energy Economics and Financial Analysis (IEEFA) Report, pp. 1-34 (2021).

108) R. Zakia and Y. Sunitiyoso, "Biomass co-firing for electricity in Indonesia: A system thinking approach," Eduvest - J. Univ. Stud., vol. 5, no. 8, pp. 9702–9710 (2025). doi:10.59188/eduvest.v5i8.50937.

109) D.F. Umar, and T. Rohayati, "Study on chemical characteristics of coal and biomass blend and the tendency of its ash deposition," Indonesian Mining Journal, 24 (2) 113–126 (2021). doi:10.30556/imj.Vol24.No2.2021.1242.

110) X.-Y. Ren, X.-B. Feng, J.-P. Cao, W. Tang, Z.-H. Wang, Z. Yang, J.-P. Zhao, L.-Y. Zhang, Y.-J. Wang, and X.-Y. Zhao, "Catalytic conversion of coal and biomass volatiles: a review," Energy & Fuels, 34 (9) 10307–10363 (2020). doi:10.1021/acs.energyfuels.0c01432.

111) L. Li, G. Liu, Y. Li, Z. Zhu, H. Xu, J. Chen, and X. Ren, "Release of sulfur and nitrogen during co-pyrolysis of coal and biomass under inert atmosphere," ACS Omega, 5 (46) 30001–30010 (2020). doi:10.1021/acsomega.0c04372.

112) H. Wei, S. Zhu, Y. Mao, J. Gao, Z. Shen, J. Li, and H. Yang, "Research progress on the dynamic characteristics of circulating fluidized bed boilers while processing rapid variable loads," Energies (Basel), 17 (14) 3549 (2024). doi:10.3390/en17143549.

113) Q. Chen, Y. Gou, T. Wang, P. Liu, and J. Zhu, "The evolutionary path and emerging trends of circulating fluidized bed technology: an integrated analysis through bibliometric assessment and data visualization," Energies (Basel), 17 (14) 3514 (2024). doi:10.3390/en17143514.

114) M. Shahbaz, A. AlNouss, I. Ghiat, G. Mckay, H. Mackey, S. Elkhalifa, and T. Al-Ansari, "A comprehensive review of biomass based thermochemical conversion technologies integrated with co2 capture and utilisation within beccs networks," Resour Conserv Recycl, 173 105734

(2021). doi:10.1016/j.resconrec.2021.105734.

Appendix A. Standardized Data Collection Templates

(Structured in Excel/CSV formats with predefined fields)

No.	Indicator	Parameter	Explanation	Form of Data	Unit
1	Technical	Generation Capacity	The maximum output a power plant can produce under specific conditions.	Numerical capacity data	MW (megawatts)
2	Technical	Net Power Generation Heat Rate	The amount of heat input required to produce one unit of electricity, indicating plant efficiency.	Numerical, heat input-output	kJ/kWh
3	Technical	Power Plant Efficiency	The ratio of electricity generated to the energy input, representing how efficiently fuel is converted to electricity.	Percentage efficiency	%
4	Technical	Furnace Exit Gas Temperature (FEGT)	The temperature of flue gases exiting the furnace, which affects combustion and heat transfer efficiency.	Numerical temperature data	°C
5	Technical	Total Fuel Consumption	The total amount of fuel consumed over a given period to produce electricity.	Cumulative fuel usage data	metric tons/year
6	Technical	Specific Fuel Consumption (SFC)	The fuel required per unit of power generated, indicating fuel efficiency.	Numerical, consumption rate	kg/kWh
7	Technical	Biomass to Coal Ratio	The proportion of biomass used relative to coal in co-firing processes.	Ratio data	%
8	Technical	Biomass Properties (moisture, ash, carbon, etc)	The chemical and physical characteristics of biomass, impacting combustion efficiency and emissions.	Compositional analysis	% (moisture, ash, carbon)
9	Technical	Biomass Calorific Value	The energy potential of biomass per unit mass, important for determining energy output.	Calorific value data	MJ/kg
10	Technical	HHV (High Heating Value)	The total amount of heat released when a fuel is burned, including the latent heat of vaporization.	Heat value data	MJ/kg
11	Technical	Operational Flexibility	The ability of a power plant to adapt to changes in demand and fuel supply.	Performance assessment data	Qualitative/quantitative
12	Technical	Fuel Availability and Security	The reliability of biomass and coal supplies for continuous operation.	Resource availability data	Qualitative/quantitative

13	Technical	Emissions Control	Mechanisms and technologies in place to reduce pollutants emitted during energy production.	Control technology data	ppm or mg/Nm^3
14	Technical	Life Cycle Assessment (LCA)	The overall environmental impact of biomass and coal use throughout the production and consumption cycle.	LCA data and results	CO2e (carbon footprint)
15	Environment	CO2 Intensity of Electricity	Measures the CO2 emissions per unit of electricity generated.	Numerical, emission factor	kg CO2/kWh
16	Environment	CO2 Intensity of Economy	The amount of CO2 emissions produced per unit of economic output (GDP).	Numerical, emissions per GDP	kg CO2/USD
17	Environment	CO2 Emission	Total CO2 emissions from energy production and related processes.	Time-series data	metric tons CO2/year
18	Environment	Electricity Generated	Total energy output from co-firing biomass and coal.	Energy output data	GWh
19	Environment	Global Warming Potential (GWP) Reduction	Measures the reduction in GWP when biomass is co-fired with coal.	Comparative emissions data	CO2-equivalent
20	Environment	Water Footprint	The total volume of freshwater used in the energy production process.	Cumulative water usage data	cubic meters/year
21	Environment	Calorific Value of Lignite	The energy content per unit weight of lignite used in co-firing.	Energy content data	MJ/kg
22	Environment	Net GHG Emission	Total GHG emissions after accounting for offsets and reductions.	Emission data	metric tons CO2e/year
23	Environment	N2O Emission	Emissions of nitrous oxide, a significant greenhouse gas, during co-firing.	Specific emissions data	metric tons N2O/year
24	Environment	Soil Loss Rates in Arable Lands	The rate of soil erosion as a consequence of biomass harvesting.	Field study data	metric tons/hectare/year
25	Environment	Emission Limit (SOx, NOx, and Particulate Matter)	Regulatory thresholds for key pollutants from power plants.	Legal/policy data	ppm

Cite: R. Jati et al., "A System Dynamics Approach to Evaluating Biomass-Coal Co-Firing in Indonesia: An Integrated Technical, Economic, Environmental and Social Framework". Evergreen, 13 (01) 18-44 (2026). https://doi.org/10.5109/7405126.

26	Environment	Soil Greenhouse Gas (GHG) Emissions	GHG emissions from soil, such as reductions in CH4 and N2O flux, due to biomass growth or decomposition.	Field measurement data	kg CO2e/year
27	Environment	Annual GHG Emissions	Total greenhouse gas emissions on an annual basis from energy production.	Yearly cumulative emissions	metric tons CO2e/year
28	Environment	Carbon Footprint	The total carbon emissions associated with the entire lifecycle of the energy production.	Comprehensive lifecycle data	metric tons CO2e
29	Economic	Carbon Price	The cost assigned to CO2 emissions, used for evaluating the economic impact of carbon emissions.	Numerical value (currency/ton of CO2)	$/t (dollars per ton)
30	Economic	Maintenance and Operational Costs	The expenses related to the operation and maintenance of power plants.	Numerical value (currency)	Currency units (e.g., $ or €)
31	Economic	Resource Cost	The total expense incurred for resources used in power production, expressed in billions of currency.	Numerical value (currency/unit of resource)	£bn (billion British pounds)
32	Economic	Cost Effectiveness	The cost per ton of carbon reduction achieved through a particular intervention.	Numerical value (cost-benefit analysis, ROI, etc.)	£/tC (pounds per ton of Carbon)
33	Economic	Current Account to GDP	The ratio of a country's current account balance to its gross domestic product, used in economic analysis.	Numerical value (ratio)	CA/GDP (ratio)
34	Economic	International Revenue	Revenue earned from international activities related to energy production or trading.	Numerical value (currency)	million $ (million dollars)
35	Economic	Power Plant Capacity	The maximum amount of power that a plant can produce, important for assessing the scale of operations.	Numerical value (MW)	MW (megawatts)
36	Economic	Biochar Yield	The amount of biochar produced per unit of biomass input during co-firing.	Numerical value (mass of biochar/mass of biomass)	kg/kg

37	Economic	Fuzzy Biochar Limit	The estimated upper limit of biochar production, accounting for uncertainties.	Numerical range or statistical distribution	Mt/y (million tons per year)
38	Economic	Sequestration Factor	The amount of CO2 that can be sequestered per unit of biochar produced.	Numerical value (mass of CO2 sequestered/mass of biomass)	Mt CO2/Mt of biochar
39	Economic	Biomass Fuel Pellet Production Cost	The cost involved in producing biomass fuel pellets, a crucial economic factor in co-firing analysis.	Numerical value (currency/ton of pellets)	$/ton
40	Economic	Investment Indicator – EcICAPEX	Represents the capital expenditure per unit of energy produced, an investment performance metric.	Numerical value (currency)	EUR per kWh
41	Economic	Energy Costs Indicator – EcIOPEX	The operational expenditure per unit of energy produced, indicating cost efficiency.	Numerical value (currency/unit of energy)	EUR per kWh
42	Social	Land-Use Issues	The area required for biomass cultivation or related energy production facilities.	Qualitative descriptions, maps or geospatial datasets	ha (hectares)
43	Social	Distances Between Biomass Sources and Power Plants	The distance affecting transport costs and logistics in supplying biomass to power plants.	Numerical data (distance in km or miles) or spatial data (maps or geospatial datasets)	km (kilometers)
44	Social	Land Use, Land Cover	Analysis of land allocated for different purposes and its impact on sustainability and ecosystem.	Spatial data (maps or geospatial datasets)	Qualitative/quantitative
45	Social	Diversity Indicator	A measure of biodiversity or ecological variation in areas used for biomass production.	Numerical index or qualitative description	Index value
46	Social	Development of Industry	The progress and expansion of industries related to biomass and renewable energy sectors.	Qualitative descriptions, economic indicators	Qualitative/quantitative
47	Social	Potential Job Creation for Biomass	The number of jobs that could be created as a result of increased biomass production and use.	Numerical estimates (number of jobs)	Number of jobs

48	Social	Social Factors (e.g., Green Image, Social Acceptance)	Social metrics including public perception, job training, social development, and community impact.	Qualitative descriptions, surveys, social media analysis	Qualitative/quantitative
49	Social	Local Zoning Law	Legal regulations that define land use and permissible activities within specific local areas.	Qualitative descriptions, legal documents	Policy/legal documentation

Appendix B. Data Sourcing & Validation Protocol

Triangulation Approach (cross-verification via 3 independent sources):

Data	Primary Source	Secondary Source	Tertiary Source	Validation Method
Policy Parameters	Government decrees	Stakeholder interviews	PLN sustainability reports	Triangulation and content validation
Technical Parameters	On-site measurements	PLN operational reports	Academic literature	Re-testing 10% random samples
Environment Parameters	Lab testing	PLN sustainability reports	Academic literature	Re-testing 10% random samples
Economic Parameters	PLN operational reports	Stakeholder interviews	National energy price statistics / academic literature	Triangulation and time-series consistency check
Social Parameters	Stakeholder questionnaire	Stakeholder interviews	Academic literature	Triangulation and content validation