

Strategic Analysis Of Biomass Co-Firing Implementation In Coal-Fired Power Plant To Support Net Zero Emissions Using Soft System Methodology

Analisis Strategi Implementasi Co-Firing Biomassa Pada Pembangkit Listrik Tenaga Uap Dalam Mendukung Net Zero Emission Menggunakan Soft System Methodology

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ABSTRACT

This study aims to analyze the existing conditions of the operational, logistical, and environmental systems at PT XYZ, identify the key success factors, and formulate a conceptual model for a biomass co-firing implementation strategy. The research employs a qualitative method with a Soft System Methodology (SSM) approach to untangle the complex and unstructured problem situation (*messy problem*). Data collection was conducted through field observations and in-depth interviews with key informants from power plant management, logistics, and environmental teams. The systemic analysis progressed through the stages of Rich Picture, CATWOE analysis, Root Definition, and Conceptual Model development. The results indicate that PT XYZ is not yet fully prepared to implement biomass co-firing directly due to technical boiler assessment requirements, the absence of a structured biomass supply chain, and regulatory uncertainties. Through the SSM approach, a conceptual model was successfully designed as a strategic recommendation to enhance supply chain governance, modify operational infrastructure, and ensure regulatory compliance.

Keywords: Biomass Co-Firing, Steam Power Plant (PLTU), Net Zero Emission, Soft System Methodology (SSM), Logistic Supply Chain.

ABSTRAK

Penelitian ini bertujuan untuk menganalisis kondisi eksisting sistem operasional, logistik, dan lingkungan di PT XYZ, mengidentifikasi faktor-faktor penentu keberhasilan, serta menyusun model konseptual strategi implementasi *co-firing* biomassa. Metode penelitian yang digunakan adalah kualitatif dengan pendekatan *Soft System Methodology* (SSM) untuk mengurai situasi masalah yang tidak terstruktur (*messy problem*). Pengumpulan data dilakukan melalui observasi lapangan dan wawancara mendalam bersama informan kunci dari manajemen *power plant*, logistik, dan tim lingkungan. Analisis sistem dilakukan melalui tahapan *Rich Picture*, analisis CATWOE, *Root Definition*, dan penyusunan Model Konseptual. Hasil penelitian menunjukkan bahwa PT XYZ belum sepenuhnya siap untuk mengimplementasikan *co-firing* biomassa secara langsung disebabkan oleh perlunya kajian teknis boiler, belum terbentuknya rantai pasok biomassa yang terstruktur, serta adanya ketidakpastian regulasi. Melalui pendekatan SSM, dirumuskan model konseptual sebagai rekomendasi strategi untuk memperkuat tata kelola rantai pasok, modifikasi infrastruktur operasional, dan pemenuhan kepatuhan regulasi lingkungan.

Kata Kunci : *Co-Firing* Biomassa, PLTU, Net Zero Emission, Soft System Methodology (SSM), Rantai Pasok Logistik

1. Introduction

Global climate change challenges have forced the energy sector to undergo a major transformation toward sustainable practices. As one of the largest emitters of greenhouse gases, coal-fired steam power plants (PLTU) face tremendous pressure to reduce their carbon footprint in line with the Indonesian government's commitment to achieving Net Zero Emission (NZE). One of the most viable short-to-medium-term solutions without rebuilding entirely new

infrastructure is the implementation of biomass *co-firing* technology, which substitutes a portion of coal with renewable organic materials.

However, implementing *co-firing* is not merely a technical modification. It represents a highly complex corporate ecosystem transformation involving multi-stakeholder interests, operational adjustments, multi-source logistical challenges, and strict environmental regulations. PT XYZ, a prominent company operating a PLTU infrastructure, is currently attempting to integrate biomass *co-firing* into its core operations. Preliminary evaluations indicate significant gaps in readiness, such as fluctuating biomass feedstock availability, technical limitations of existing pulverized coal boilers, and unresolved regulatory standards.

Because this problem involves complex human activities, technical constraints, and organizational dynamics, it can be classified as an unstructured problem situation or a "*messy problem*". Conventional hard-system engineering approaches are insufficient to solve such issues. Therefore, this study utilizes *Soft System Methodology* (SSM) as a systemic tool to explore, analyze, and construct a comprehensive conceptual strategy. The objective of this research is to evaluate the existing conditions of the operational, logistical, and environmental systems at PT XYZ, discover the crucial success elements, and construct an actionable conceptual model to guide the company's energy transition.

2. Literature Review

Biomass Co-Firing Technology

Biomass *co-firing* is the practice of burning biomass alongside coal in traditional coal-fired boilers. According to energy transition literature, *co-firing* provides an immediate reduction in CO₂, SO_x, and NO_x emissions because biomass is considered carbon-neutral. In a pulverized coal boiler system like the one utilized by PT XYZ, wood pellets, sawdust, or agricultural residues can be introduced into the combustion chamber. However, technical constraints such as lower energy density, slagging, fouling, and higher moisture content of biomass require rigorous operational management.

Supply Chain Logistics in Energy Transition

The reliability of a *co-firing* plant heavily relies on its logistical system. Unlike coal, which has an established and centralized supply chain, biomass supply chains are often decentralized, seasonal, and fragmented. Ensuring supply continuity, maintaining strict storage standards to prevent degradation, and verifying supplier legality are critical components of logistical readiness.

Soft System Methodology (SSM)

Soft System Methodology, originally developed by Peter Checkland, is an approach used to model and solve complex, messy real-world problems where there is no clear consensus on what the actual problem is. SSM consists of seven sequential steps (or condensed into four main stages in modern applications): entering the problem situation, expressing it through *Rich Pictures*, formulating *Root Definitions* via CATWOE analysis, developing *Conceptual Models*, comparing models with reality, and defining desirable and feasible changes. This methodology allows researchers to incorporate human behavior, organizational culture, and technical structures into a unified solution. **Employee Performance**

3. Research Methods

This study uses a qualitative research design with a systemic action-oriented approach based on *Soft System Methodology* (SSM). The research was conducted at the power generation facilities of PT XYZ.

Data collection relied on primary and secondary sources. Primary data were gathered through extensive field observations and in-depth, semi-structured interviews with key informants. The selected key informants included the Manager and Superintendent of the Power Plant Department, representatives from the Fuel Procurement/Logistics Team, and specialists from the Environmental Team. This purposive selection ensured that all affected subsystems (operational, supply chain, and regulatory) were adequately represented. Secondary data included technical boiler specifications, fuel logs, and environmental compliance reports.

The data analysis followed the structured stages of SSM:

1. **Expressing the Problem Situation:** Building a *Rich Picture* based on field data to map the interactions, conflicts, and challenges between PT XYZ's departments and external partners.
2. **Formulating Root Definitions:** Constructing purposeful system definitions using the **CATWOE** framework:
 - **C (Customers):** Who benefits or suffers from the system?
 - **A (Actors):** Who performs the transformation activities?
 - **T (Transformation):** What is the input-to-output shift?
 - **W (Weltanschauung):** What worldview makes this system meaningful?
 - **O (Owners):** Who can stop or authorize the system?
 - **E (Environmental Constraints):** What external limits must be accepted?
3. **Developing Conceptual Models:** Generating a structured logical model of the human activity system necessary to achieve the transformation.

4. Results and Discussions

Problem Situation Considered Problematic

Based on field observations, document reviews, and in-depth interviews with key stakeholders across the power plant operational, fuel logistics, and environmental management sectors, a complex and multidimensional "messy problem" was identified. While the power plant's existing operations heavily rely on coal due to its high calorific value, stable availability, and structured long-term contracts, global and national pressures—such as the Paris Agreement and Net Zero Emission targets—demand a structural transition toward sustainable energy.

Biomass *co-firing* utilizing local agricultural waste (e.g., corn cobs and palm oil waste from the Sumbawa region) presents a viable decarbonization pathway. However, its implementation is hindered by critical bottlenecks across three primary interrelated subsystems:

- **Logistical Constraints:** There is a severe lack of data regarding the large-scale volume availability and continuity of biomass supply. Furthermore, supplier capabilities to meet sustained power plant demands remain unverified, and the transportation framework from the source to the PLTU is undefined.
- **Operational Adaptations:** Integrating biomass introduces technical challenges due to its lower energy density and distinct physical properties compared to coal. This directly impacts boiler combustion performance, fuel handling mechanisms, dedicated storage space requirements, and combustion residue management.
- **Regulatory Uncertainties:** The absence of explicit, standardized technical guidelines governing emission limits for *co-firing* systems creates a regulatory vacuum, forcing the company to undergo extensive, prolonged internal feasibility studies.

Because these challenges intertwine technical limitations, supply chain vulnerabilities, and shifting regulatory frameworks across multiple stakeholders (operations, logistics, environmental teams, suppliers, and regulators), the situation cannot be solved through linear methods. Therefore, using *Soft System Methodology* (SSM) is critical to map these multi-actor dynamics, expose the root causes, and design structurally desirable and culturally feasible interventions

Problem Situation Expressed (Rich Picture)

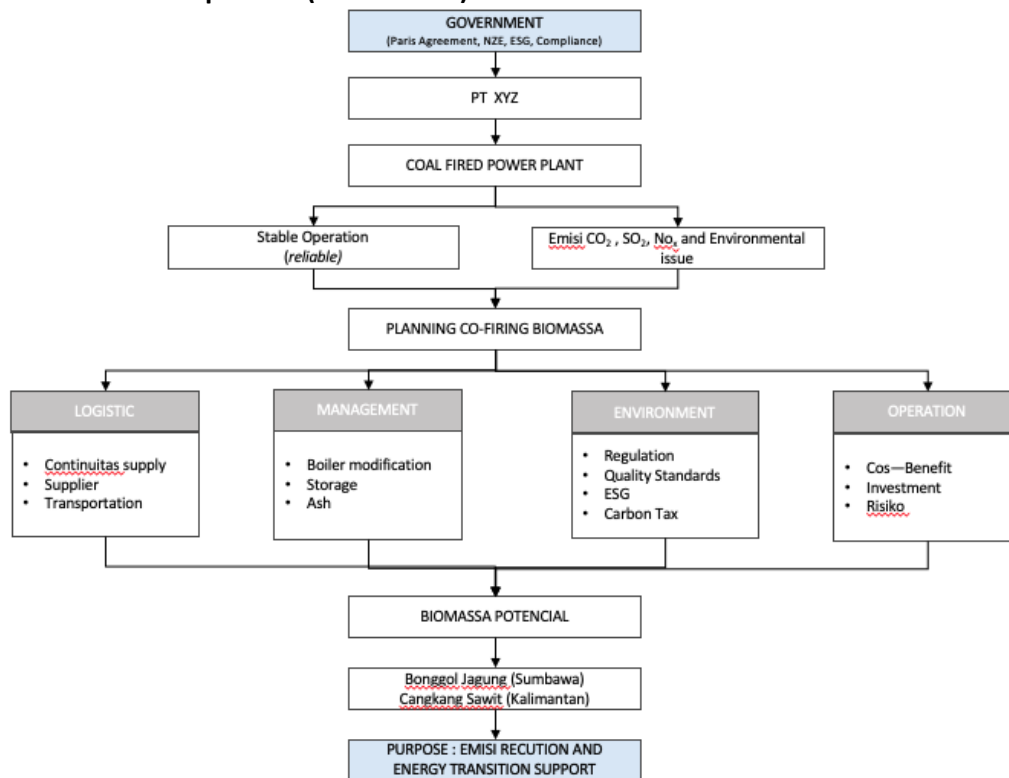


Fig. 1. Rich Picture

Following the identification of the problem situation, the next stage in Soft System Methodology (SSM) involves expressing the problem context through a Rich Picture. This systemic tool visually maps the real-world operational environment, displaying the interactions among actors, institutional bottlenecks, conflicting perspectives, and critical external pressures. The Rich Picture structurally maps out a highly complex web of interactions across multiple subsystems and actors, each driven by distinct operational mandates and perspectives:

- **External Pressures and Corporate Commitments:** The system is continuously shaped by macro-level external forces, including the Indonesian government's commitment to the Paris Agreement, national carbon reduction policies, and evolving environmental standards. These factors compel the organization to pursue sustainability initiatives such as biomass *co-firing* utilizing local agricultural residues (e.g., corn cobs and palm oil waste).
- **Operational Subsystem (PLTU Generation):** The current power generation system heavily relies on coal due to its proven operational reliability and mature, highly structured supply chain. The generation team focuses primarily on maintaining technical performance, ensuring that introducing biomass will not induce adverse effects like slagging, fouling, or boiler efficiency degradation.
- **Logistical Subsystem (Fuel Procurement):** While the Environmental Team views *co-firing* as an immediate opportunity for emissions abatement and waste product transformation, the Logistics Team raises critical concerns regarding supply chain maturity. Their focus centers on feedstock volume availability, long-term supply continuity, institutional supplier legality, and the lack of an established regional transportation framework.
- **Corporate Management and Regulators:** Corporate management must balance these conflicting internal demands, evaluating the feasibility of *co-firing* from holistic strategic, operational, and financial sustainability angles. Concurrently, government regulators maintain a persistent push for lower emission baselines through shifting energy policies.

Ultimately, the Rich Picture synthesizes the operational realities of the PLTU, the unformed biomass supply chain, stringent environmental demands, and overall corporate sustainability targets. It highlights that the delay in *co-firing* deployment stems not from a lack of conceptual intent, but from the systemic friction among these diverse stakeholder objectives, which requires a structurally desirable and culturally feasible resolution.

Root Definition and CATWOE Analysis

Root Definition

Based on the problem identification, field observations, document reviews, and in-depth interviews with key informants from the Power Plant, Logistics, and Environmental subsystems, the implementation of biomass *co-firing* presents a highly complex, multidimensional challenge. These bottlenecks extend beyond technical combustion limits to include supply chain logistics, infrastructural readiness, environmental regulations, feedstock availability, and long-term supply sustainability.

To systematically address these interrelated factors and design realistic operational improvements, a purposeful human activity system must be defined. Guided by the principles of Soft System Methodology (SSM), the **Root Definition** for this research is formulated as follows:

"A system owned and operated by the company to design a strategic framework for implementing biomass co-firing by developing a sustainable supply chain logistics system, supported by power plant operational readiness and compliance with environmental regulations, in order to reduce coal dependency, advance corporate sustainability goals, and align with national energy transition policies."

This Root Definition articulates the intended system designed to transform the current baseline state—which is heavily dependent on coal—into a more adaptive, resilient system that successfully integrates biomass-based alternative energy while maintaining a balanced focus on technical, environmental, and operational parameters.

CATWOE Analysis

To clarify and contextualize the formulated Root Definition, a CATWOE analysis was conducted. This framework breaks down the purposeful human activity system into six critical elements: Customers (C), Actors (A), Transformation process (T), Worldview (W), Owners (O), and Environmental constraints (E).

1. Customers (C)

Customers refer to the stakeholders who directly benefit from or are affected by the proposed systemic transformation. In this study, the primary customers include:

- **The Company:** Gains a viable energy transition roadmap, minimized coal reliance, and enhanced corporate sustainability positioning.
- **Power Plant Department:** Secures alternative fuel streams to guarantee long-term operational resilience and future fuel diversity.
- **The Government:** Receives industry-level support toward achieving national greenhouse gas reduction targets and executing energy transition policies.
- **The Community:** Benefits from localized emissions abatement and the optimization of previously underutilized agricultural or organic waste.
- **Biomass Business Entities/Suppliers:** Open new market pathways by acting as commercial alternative fuel providers for the power generation sector.

2. Actors (A)

Actors are the internal and external agents responsible for executing the transformation processes within the system. They include:

- **Power Plant Department:** Handles technical evaluations regarding *co-firing* feasibility, boiler adjustments, combustion behavior, emission controls, and overall plant performance impacts.
- **Logistics Department:** Manages biomass procurement, vendor selection, regional transportation networks, fuel storage, and supply stream continuity.
- **Environmental Department:** Conducts environmental impact assessments, monitors regulatory compliance, maps emission inventories, and spearheads corporate sustainability programs.
- **Biomass Suppliers:** Act as raw material partners ensuring feedstock quality and volume requirements align with plant parameters.
- **Corporate Management:** Serves as the ultimate strategic decision-makers regarding organizational investments and *co-firing* policies.

3. Transformation Process (T)

The transformation process captures the structural shift from the current baseline input (unstructured problem situation) to the desired systemic output.

$$\text{Input (Baseline State)} \rightarrow \text{Output (Transformed State)}$$

- **Input Conditions:** Complete structural dependency on coal; absence of a biomass logistics framework; lack of dedicated biomass storage infrastructure; insufficient technical feasibility studies regarding *co-firing*; unverified supply market continuity; and a lack of a contextualized deployment model.
- **Output Conditions:** A fully mapped biomass logistics model; actionable technical recommendations for *co-firing*; defined secondary infrastructure requirements; clear risk mitigation matrixes; reduced coal consumption; and accelerated corporate sustainability integration.

Summarized Transformation Statement: "To transform an operational system completely dependent on coal into a structurally adaptive system equipped for integrated biomass co-firing deployment."

4. Worldview / Weltanschauung (W)

The Worldview represents the underlying philosophy or perspective that makes this system highly meaningful and necessary:

"Biomass co-firing presents a highly viable, near-term energy transition pathway that immediately mitigates fossil fuel reliance and advances corporate environmental sustainability targets without requiring an entirely new power plant infrastructure."

This perspective aligns directly with Indonesia's commitments to the Paris Agreement and national Net Zero Emission timelines, forcing heavy industries to systematically embrace carbon reduction pathways.

5. Owners (O)

Owners hold the institutional authority to initiate, alter, or completely halt the proposed human activity system:

- **Corporate Management:** Possesses absolute jurisdiction to authorize *co-firing* operations, approve infrastructure capital expenditures (CapEx), dictate procurement strategies, and align organizational energy targets. The system cannot progress to field deployment without their explicit authorization.

6. Environmental Constraints (E)

Environmental constraints are external forces, bottlenecks, or limitations that significantly influence systemic success but lie outside the direct control of the organization:

- **Biomass Market Volatility:** Gaps in data regarding the sustained, seasonal availability of local feedstocks like corn cobs or palm residues in the region.
- **Shifting Policy Regimes:** Evolving state policies on carbon pricing, emission baselines, and tax credits that could shift financial feasibility.
- **Regional Logistics Deficits:** Fragmented local transport infrastructure and storage bottlenecks between rural agricultural sources and the PLTU site.
- **Feedstock Fuel Variations:** Natural inconsistencies in calorific value, sulfur contents, ash fusion temperatures, and moisture levels of the raw biomass.
- **Technological Legacies:** The existing pulverized coal boiler was not natively engineered for organic biomass materials, demanding intensive technical adjustments.
- **Socio-Economic Dynamics:** Potential local community resistance if the supply chain favors external biomass providers over regional agricultural labor.

Conceptual Model

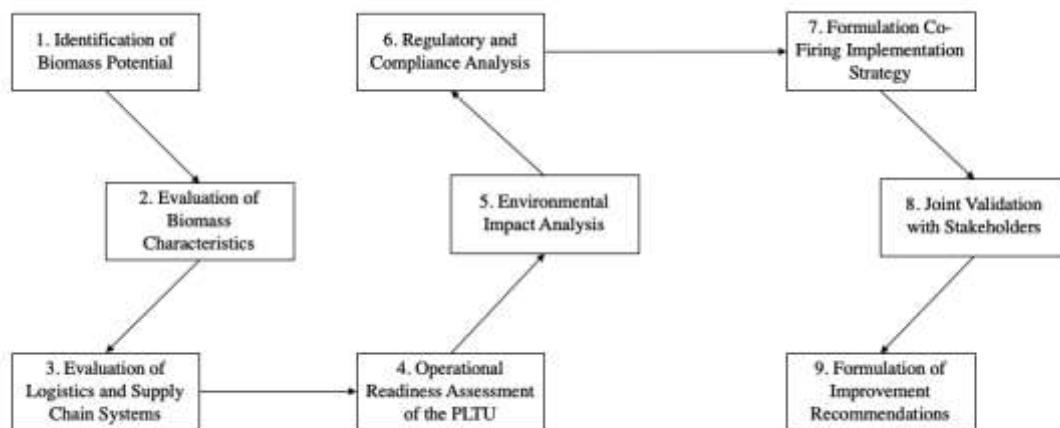


Fig. 2. Conceptual Model

The Conceptual Model is systematically derived from the previously formulated CATWOE analysis and Root Definition. This logical model visualizes the minimum necessary human activity systems required to effectively operationalize the biomass *co-firing* strategy at the PLTU.

The primary objective of this model is to build a sustainable biomass logistics infrastructure that supports *co-firing* as an integrated component of the company's energy transition and emissions abatement agenda. Crucially, this conceptual model does not reflect the flawed current reality of the company; rather, it establishes an ideal systemic baseline to serve as the foundation for defining structurally desirable and culturally feasible interventions.

Synthesized from stakeholder interviews, field observations, and corporate documentation, nine core activity blocks were mapped out to drive the *co-firing* implementation system:

1. Biomass Potential Identification
2. Biomass Characteristics Evaluation
3. Logistics and Supply Chain System Evaluation
4. PLTU Operational Readiness Assessment
5. Environmental Impact Analysis
6. Regulatory and Compliance Analysis
7. Formulation of the Co-Firing Implementation Strategy
8. Multi-Stakeholder Validation

9. Development of Feasible and Desirable Recommendations

Comparison Between Real World and Conceptual Model

The comparative analysis between the conceptual model and the actual operational reality reveals that while the company has established an initial awareness regarding the critical importance of biomass utilization for energy transition and emission abatement, the implementation of biomass *co-firing* remains strictly conceptual and has not yet advanced to further development stages. Internal discussions have taken place regarding the potential use of corn cobs, palm kernels, and Refuse-Derived Fuel (RDF) as alternative energy sources; however, systematic integration has not materialized.

The comparison uncovers critical structural gaps across three core subsystems:

- **Logistical Gaps:** The most substantial discrepancy lies in the complete absence of an established biomass supply chain system capable of ensuring long-term supply continuity. Interviews with the logistics department confirm that the company lacks adequate data concerning regional supplier capacities, multi-modal distribution methods, and long-term legal contracting mechanisms. Because the reliability of *co-firing* operations depends directly on an uninterrupted fuel stream, this unformed supply chain represents the primary institutional bottleneck.
- **Operational Gaps:** The existing PLTU infrastructure is fully engineered and optimized for coal combustion. The utilization of a pulverized coal boiler introduces severe technical constraints due to the contrasting physical and chemical profiles of biomass compared to traditional fossil fuels. Furthermore, a critical data vacuum exists regarding empirical fuel properties—such as specific calorific values, sulfur levels, moisture content, and ash fusion temperatures—preventing the engineering team from conducting baseline assessments on combustion efficiency, heat rates, or plant asset performance impact.
- **Environmental Gaps:** While the company demonstrates high corporate commitment toward sustainability programs, national energy transition mandates, and global climate goals, there is an absence of localized environmental accounting studies. The organization has not yet quantified the empirical emissions abatement potential that *co-firing* deployment would yield. This lack of quantitative data is exacerbated by technical regulatory uncertainties regarding point-source emission limits for multi-fuel combustion in legacy power plants.

In conclusion, the comparative assessment indicates that while the opportunity to develop biomass *co-firing* at the facility is highly viable, it requires comprehensive preparatory studies across logistical networks, mechanical operations, and environmental governance frameworks.

5. Conclusion

The application of *Soft System Methodology* successfully uncovers the multi-layered complexities of implementing biomass *co-firing* at PT XYZ. The study finds that the company is currently in a transitional state and requires systemic improvements before fully deploying the technology. Operationally, technical interventions and rigorous boiler efficiency assessments are mandatory. Logistically, PT XYZ must establish institutionalized supply chain networks to overcome biomass supply volatility and ensure supplier compliance. Environmentally, clear compliance pathways must be established alongside policymakers. The formulated conceptual model provides a robust strategic blueprint for PT XYZ to execute a sustainable, efficient, and legally compliant energy transition.

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