A Conceptual Framework for the Selection of Biomass Alternatives for Coal Co-firing using Multi-Criteria Decision Making (MCDM) Approach

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Abstract. The increasing demand for sustainable energy and the need to reduce carbon emissions have driven the implementation of biomass co-firing in coal-fired power plants. Selecting appropriate biomass alternatives for co-firing is a complex decision involving multiple technical, economic, environmental, social, and regulatory considerations. This study aims to develop a conceptual framework for selecting biomass alternatives for co-firing in coal power plants. The framework integrates Analytic Hierarchy Process (AHP) and Structural Equation Modeling-Partial Least Squares (SEM-PLS) to identify and prioritize key selection criteria. The model consists of five main criteria technical, economic, environmental, social, and policy/regulation with a total of 14 validated sub-criteria. The dependent variable, Selection of Biomass Alternative, is measured by four biomass types: Rice Husk, Wood Pellet, Palm Kernel Shell, and Sawdust. The proposed framework provides a comprehensive tool to support decision-making and ensure the sustainable implementation of biomass co-firing.

Keywords: *Biomass Co-firing, Multi-Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP), SEM-PLS, Renewable Energy.*

1 Introduction

The global pursuit of sustainable energy has become increasingly urgent in the face of climate change and international commitments to reduce greenhouse gas (GHG) emissions. Coal-fired power plants, while essential for energy security in many developing countries, are responsible for a significant share of CO_2 emissions. According to the International Energy Agency (IEA), coal combustion accounts for nearly 40% of global carbon emissions from the energy sector [1]. Indonesia, as one of the world's largest coal producers and consumers, faces a dual challenge: ensuring reliable electricity supply while meeting its climate targets under the Paris Agreement [2].

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In response to this challenge, the Indonesian government has initiated several strategies, including the co-firing of biomass with coal in existing coal-fired power plants. This approach offers a practical and cost-effective solution by partially substituting coal with biomass, such as wood pellets, palm kernel shells, and rice husks [3]. The advantage of biomass co-firing lies in its ability to reduce net CO_2 emissions without requiring extensive modifications to existing power plant infrastructure [4]. However, successful implementation depends on selecting biomass alternatives that are not only technically feasible but also economically viable and environmentally sustainable [5].

The selection process is inherently complex due to the multi-dimensional nature of biomass characteristics. Key criteria include the technical properties of biomass, such as calorific value, moisture content, and combustion efficiency [6], economic considerations, including fuel cost, supply chain logistics, and availability [7], and environmental impacts, such as life cycle emissions and ash content [8]. Additionally, social factors such as community acceptance, policy alignment, and potential job creation further complicate the decision-making landscape [9]. Traditional decision-making approaches often fail to capture these complexities, leading to decisions that may appear optimal in the short term but are unsustainable in the long run [10]. To address this complexity, Multi-Criteria Decision Making (MCDM) methods have gained prominence. MCDM provides a structured approach to evaluate and prioritize alternatives based on multiple, and often conflicting, criteria [3]. Among these, the Analytic Hierarchy Process (AHP) stands out for its simplicity and effectiveness in deriving weightings and rankings through pairwise comparisons [5]. However, while AHP is powerful in prioritizing criteria and alternatives, it does not inherently address the interrelationships between criteria, which can be critical in complex systems like biomass co-firing [11].

Several studies have explored biomass selection using MCDM methods. Filho et al. applied AHP and GIS to assess the feasibility of using crop residues for electricity production in Brazil, focusing primarily on technical and environmental criteria [5]. Similarly, Howari et al. employed a hybrid AHP-TOPSIS model to rank biomass waste materials based on pyrolysis performance and emission parameters [6]. Lopes et al. used TOPSIS to select CO_2 and H_2 sources for ch Inventory Management Efficiency Strategy at UID Banten emical production, introducing economic and technical dimensions but focusing on non-biomass energy sources [10]. Other notable works include Akpahou and Odoi-Yorke, who applied CRITIC and EDAS methods to prioritize renewable energy resources in Benin, highlighting social and economic factors [9]. Akbaş and Bilgen utilized ANP to determine strategic energy policy priorities in Turkey [7], while Wang et al. combined FANP, TOPSIS, and GIS for optimal location selection of waste-to-energy plants [8].

While these studies have advanced the field by integrating various MCDM methods, they exhibit certain limitations. Most focus on ranking alternatives but do not map the intricate relationships among criteria [11]. Additionally, few studies integrate advanced statistical techniques such as Structural Equation Modeling (SEM), which can validate and analyze causal relationships between criteria—a critical aspect for a deeper understanding of decision dynamics [11]. This study aims to fill a crucial void by proposing a conceptual framework that integrates AHP and SEM-PLS. The framework not only enables the ranking of biomass alternatives but also explores and validates the relationships among criteria (e.g., how fuel cost may influence environmental impact or how logistical considerations affect technical feasibility) [3]. This dual-layered approach ensures a more comprehensive and insightful decision-making model that is directly applicable to coal-fired power plants, particularly in the Indonesian context. The main objective of this study is to develop a conceptual framework for selecting biomass alternatives for coal co-firing in coal-fired power plants by integrating multi-criteria decision-making methods to support sustainable energy implementation.

2 Methodology

This study adopts a qualitative approach to develop a conceptual framework for selecting biomass alternatives for coal co-firing. The methodology comprises three main stages. First, a systematic literature review (SLR) was conducted to identify and synthesize key selection criteria from previous studies on biomass energy and co-firing applications [5]–[8], [14]–[16]. Second, expert consultation was used to validate and refine the criteria, ensuring relevance and applicability to the Indonesian context [2]. Third, the framework structure was formulated by integrating into the Analytic Hierarchy Process (AHP) to establish hierarchical relationships among criteria [6], [7], [15], and Structural Equation Modeling-Partial Least Squares (SEM-PLS) to represent potential causal relationships among constructs [5], [14]. The final framework maps five main criteria technical, economic, environmental, social, and policy/regulation each supported by relevant sub-criteria, linking them to the selection of biomass alternatives as the dependent variable. The overall flowchart of this study is presented in Figure 1.

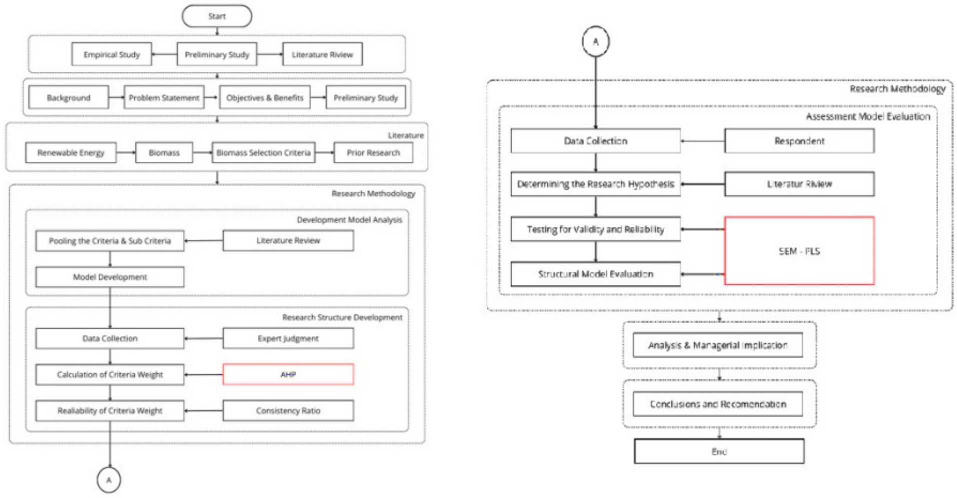

Figure 1 Research Flowchart

3 Results and Discussion

3.1 Results

3.1.1. Identified Criteria and Sub-Criteria

The results of this study consist of the identification and synthesis of key selection criteria and sub-criteria for biomass alternatives for coal co-firing. Based on a systematic literature review [5]–[8], [14]–[16] and expert validation [2], five main criteria were identified: technical, economic, environmental, social, and policy/regulation. Each criterion is represented by a set of relevant sub-criteria, as presented in Table 1.

Table 1 summarizes the selected criteria and sub-criteria derived from multiple studies including Filho et al. [5], Howari et al. [6], Akbaş and Bilgen [7], Yaman et al. [14], Ahmad and Tahar [15], and Cobuloglu and Buyuktahtakin [16]. These studies highlight the importance of calorific value, combustion efficiency, ash content, raw material price, logistics cost, CO2 emissions, and public acceptance, among others, as key factors influencing the selection of biomass alternatives.

Table 1. Results Identified Criteria and Sub-criteria

No.	Criteria	Sub-Criteria	Source
1	Technical	Calorific Value	Filho et al. (2025) [5]; Howari et al. (2023) [6]; Yaman (2024) [14]
		Combustion Efficiency	Filho et al. (2025) [5]; Howari et al. (2023) [6]; Yaman (2024) [14]; Ahmad & Tahar (2014) [15]
		Ash Content	Howari et al. (2023) [6]; Wang et al. (2018) [8]; Yaman (2024) [14]
2	Economic	Raw Material Price	Akbaş & Bilgen (2017) [7]; Shahraki et al. (2020) [11]; Cobuloglu & Buyuktahtakin (2015) [16]
		Logistics Cost	Filho et al. (2025) [5]; Akbaş & Bilgen (2017) [7]; Yaman (2024) [14]; Cobuloglu & Buyuktahtakin (2015) [16]
		Distance to Plant	Filho et al. (2025) [5]; Yaman (2024) [14]
3	Environmental	CO2 Emissions	Filho et al. (2025) [5]; Howari et al. (2023) [6]; Wang et al. (2018) [8]; Yaman (2024) [14]; Cobuloglu & Buyuktahtakin (2015) [16]
		Environmental Sustainable Removal	Filho et al. (2025) [5]
		Sulfur Emissions	Howari et al. (2023) [6]; Yaman (2024) [14]
4	Social	Local Socioeconomic Impact	Filho et al. (2025) [5]; Akpahou & Odoi-Yorke (2023) [9]
		Job Creation	Ahmad & Tahar (2014) [15]; Yaman (2024) [14]
		Public Participation and Engagement	Lopes et al. (2021) [10]; Gyimah et al. (2024) [12]
5	Policy/ Regulation	Compliance with National Regulation	PLN (2020) [2]
		Support for Renewable Energy Policies	PLN (2020) [2]
		Permitting/Licensing Feasibility	PLN (2020) [2]

3.1.2. Steps of the Analytic Hierarchy Process (AHP)

The AHP method is applied to derive the relative importance weights of each criterion and sub-criterion through a pairwise comparison process. The steps of the AHP method are as follows [6], [15]:

1. Hierarchy Structure: Establish a hierarchical structure of the decision problem, consisting of the goal at the top level (biomass alternative selection), criteria at the intermediate level (technical, economic, environmental, social, policy/regulation), and sub-criteria at the lower level.

2. Pairwise Comparison Matrix: Construct pairwise comparison matrices among the elements at each level of the hierarchy using the fundamental Saaty scale (1–9) [6].

3. Normalization and Priority Weight Calculation:
   a. Normalize the matrix by dividing each element in a column by the total of that column.
   b. Calculate the priority weights by averaging the normalized values in each row.
   Normalization formula:
$$a'_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \quad (1)$$

   Weight formula:
$$w_i = \frac{\sum_{j=1}^{n} a'_{ij}}{n} \quad (2)$$

4. Consistency Check: Compute the Consistency Index (CI) and the Consistency Ratio (CR) to ensure the judgments are consistent [6].
   Consistency Index (CI):
$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (3)$$
   Consistency Ratio (CR):
$$CR = \frac{CI}{RI} \quad (4)$$
   Where RI is the random index based on the matrix size. A CR < 0.1 indicates acceptable consistency.

5. Prioritization: The final output consists of the global weights of each sub-criterion, which serve as input for the SEM-PLS analysis.

These steps provide a quantitative foundation for determining the importance of each factor in the selection of biomass alternatives, which is further analyzed using SEM-PLS to understand the causal relationships among the criteria.

3.1.3. Steps of Structural Equation Modeling (SEM-PLS)

Structural Equation Modeling using Partial Least Squares (SEM-PLS) is employed in this study to analyze and validate the causal relationships among the identified criteria and the selection of biomass alternatives. The following are the key steps involved in SEM-PLS [5], [14]:

1. Model Specification: Define the measurement model (outer model) representing the relationships between latent variables and their

indicators, and the structural model (inner model) representing the relationships among latent variables.

2. Path Model Design: Establish paths based on hypotheses linking independent latent variables (technical, economic, environmental, social, policy/regulation) to the dependent latent variable (biomass selection).

3. Outer Model Evaluation: Evaluate the reliability and validity of indicators using:
   a. Composite Reliability (CR): CR > 0.7 indicates internal consistency.
   b. Average Variance Extracted (AVE): AVE > 0.5 indicates convergent validity.
   c. Discriminant Validity (Fornell-Larcker criterion).
   Formula for CR:

$$CR = \frac{(\sum \lambda_i)^2}{(\sum \lambda_i)^2 + \sum \theta_i} \quad (1)$$

   Formula for AVE:

$$AVE = \frac{\sum \lambda_i^2}{n} \quad (2)$$

4. Inner Model Evaluation: Evaluate path coefficients and R-squared () values to assess explanatory power. Use bootstrapping to test the significance (p-values) of path coefficients.

$$R^2 = \frac{\text{Explained Variance}}{\text{Total Variance}} \quad (3)$$

5. Model Fit Assessment: Examine standardized root mean square residual (SRMR) and other goodness-of-fit indices to validate model fit.

6. Interpretation of Results: Identify significant relationships and their implications for decision-making in the context of biomass selection.

This SEM-PLS process complements the AHP-based prioritization by providing statistical validation of interdependencies among the decision criteria, ensuring a comprehensive and robust model for biomass alternative selection

3.1.4. The Developed Framework Model

The identification and validation of the key criteria and sub-criteria were synthesized into a conceptual framework. This framework integrates the selected factors into a structured model to support decision-making in selecting biomass alternatives for coal co-firing. The relationships among the criteria, sub-criteria, and the selection outcome are visually presented in Figure 1.

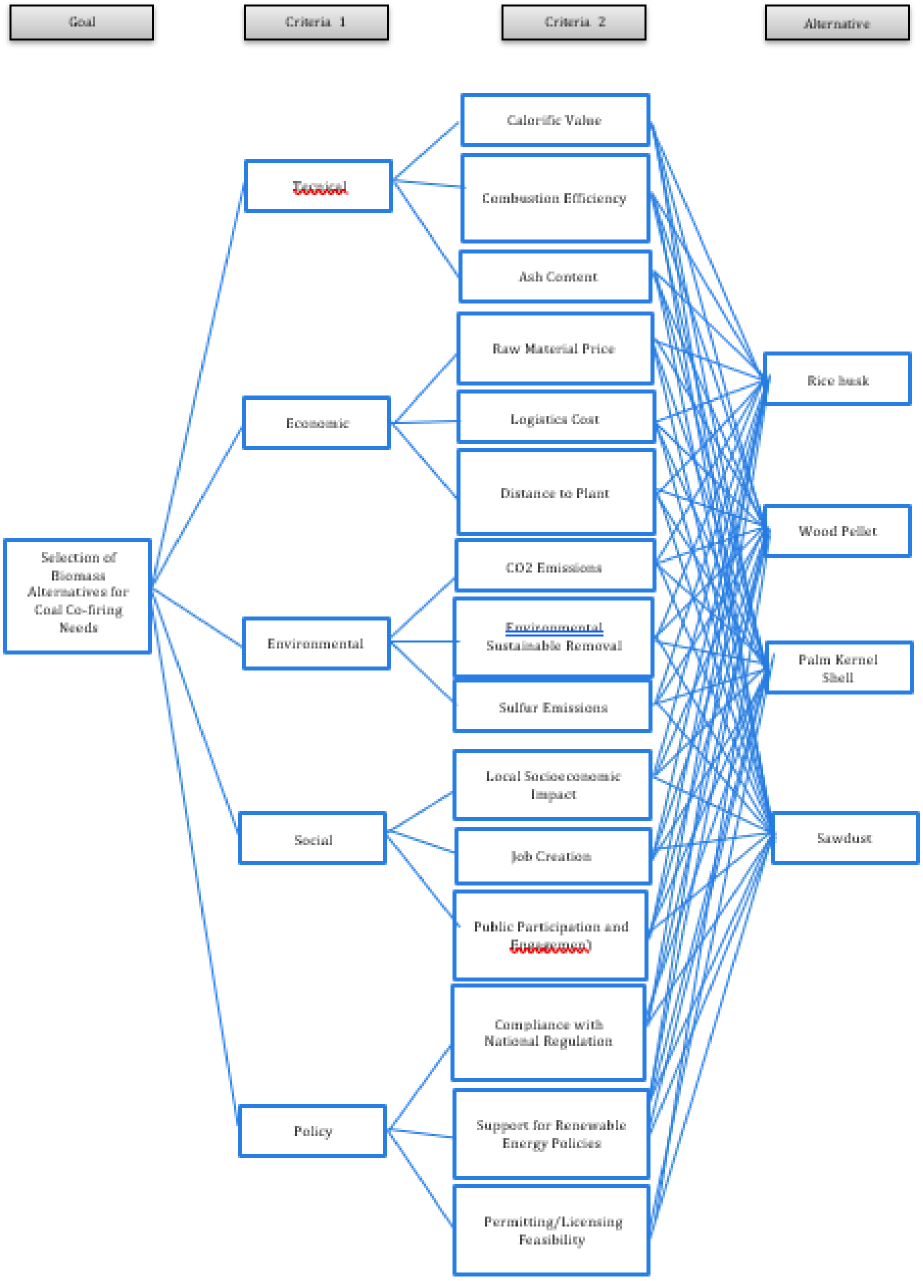

Figure 2. Development Framework Model Structure

Figure 1 illustrates the proposed conceptual framework integrating the Analytic Hierarchy Process (AHP) and Structural Equation Modeling-Partial Least Squares (SEM-PLS) for selecting biomass alternatives for coal co-firing. The framework comprises five independent latent variables technical, economic, environmental, social, and policy/regulation each represented by a set of sub-criteria identified from previous studies [5]–[8], [14]–[16]. These independent variables are hypothesized to influence the dependent variable, Selection Alternative Biomass, which is measured by four indicators: Rice Husk, Wood Pellet, Palm Kernel Shell, and Sawdust. The framework establishes both hierarchical relationships (from criteria to sub-criteria) and causal paths (from criteria to selection outcome), providing a comprehensive model for decision-making in sustainable biomass co-firing implementation.

3.2 Discussion

The conceptual framework developed in this study integrates five main criteria technical, economic, environmental, social, and policy/regulation—each supported by relevant sub-criteria derived from a systematic literature review and expert validation [5]–[8], [14]–[16]. This integration reflects the multidimensional nature of biomass alternative selection for coal co-firing, aligning with findings from previous studies that emphasized the complexity of balancing technical feasibility, economic viability, environmental sustainability, and social acceptance [6], [7], [14].

Compared to existing models, the inclusion of the policy/regulation criterion in this framework represents a significant novelty. While earlier studies such as Howari et al. [6], Akbaş and Bilgen [7], and Yaman et al. [14] have focused primarily on technical, economic, and environmental factors, this study acknowledges the critical role of regulatory compliance and policy support in ensuring successful co-firing implementation. This addition addresses a gap in previous multi-criteria decision-making models, providing a more comprehensive approach for decision-makers operating within regulated energy sectors.

Moreover, the integration of AHP and SEM-PLS methodologies offers a dual advantage: AHP facilitates the prioritization of criteria and sub-criteria, while SEM-PLS allows for the examination of causal relationships between variables. This methodological combination provides both hierarchical insights and structural validation, supporting more informed and robust decision-making.
The proposed framework serves not only as an academic contribution but also as a practical tool for stakeholders in the energy sector, particularly in Indonesia, where policy alignment and regulatory compliance are essential for sustainable biomass co-firing adoption [18].

4. Conclusion

This study has developed a conceptual framework for selecting biomass alternatives for coal co-firing by integrating the Analytic Hierarchy Process (AHP) and Structural Equation Modeling-Partial Least Squares (SEM-PLS). The framework incorporates five main criteria technical, economic, environmental, social, and policy/regulation supported by a total of 14 validated sub-criteria identified through a systematic literature review and expert validation. By linking these criteria to the dependent variable, Selection Alternative Biomass, measured by four biomass types (Rice Husk, Wood Pellet, Palm Kernel Shell, and Sawdust), the framework provides a comprehensive tool for decision-making.

The inclusion of policy/regulation as an independent criterion represents a novel contribution, addressing gaps in previous models that focused solely on technical, economic, and environmental aspects. This framework can serve as a decision-support system for policymakers, power plant operators, and other stakeholders in implementing sustainable biomass co-firing strategies.

Future research is recommended to empirically test and validate the framework using primary data from case studies or pilot projects to enhance its applicability and generalizability.

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