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System Dynamics for Policy Simulation of FABA (Fly Ash and Bottom Ash) Waste Utilization

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Abstract. Fly Ash and Bottom Ash (FABA) are by-products of coal combustion in power plants that pose environmental risks if not properly utilized. This study develops a System Dynamics model to evaluate policy scenarios for FABA utilization at the Nagan Raya coal-fired power plant, which produces an average of 2,295 tons of FABA per month. The model is based on historical data from 2016 to 2024 and simulates policy interventions for the 2025–2030 period, including biomass co-firing, public awareness campaigns, and subsidies for industrial users.
The simulation results for 2030 show that the combined policy scenario successfully reduces stored FABA from 98,352 tons to 37,011 tons and increases FABA utilization from 1,050 tons/month to 1,850 tons/month. CO_2 emission reductions also increase significantly, from 1,570 tons/month to 10,220 tons/month. The policy requires industrial subsidies of IDR 130 million/month and socialization costs of IDR 30 million/month. This study demonstrates that simulation-based waste policy modeling can effectively support the transition strategy toward achieving Indonesia's Net Zero Emission 2060 target.

Keywords: *FABA, system dynamics, coal-fired power plant, waste utilization, subsidy policy*

1 Introduction

Fly Ash and Bottom Ash (FABA) are waste products resulting from coal combustion in industrial processes, particularly at coal-fired power plants (PLTU). As national energy demand continues to rise and dependency on coal as a primary energy source remains high, the volume of FABA produced has increased significantly each year. The large-scale generation of FABA poses serious environmental management challenges. If not properly handled, FABA has the potential to contaminate air, soil, and groundwater—especially when it is merely stored in ash ponds without further processing (Basu & Lee, 2019). FABA also holds economic potential as an alternative raw material in the construction sector. Several studies have shown that FABA can be utilized in the production of cement, concrete, bricks, paving blocks, and for soil stabilization in road construction (Singh et al., 2020; Wang et al., 2022). This potential aligns with the circular economy approach, which emphasizes using waste as a new resource. In the context of Indonesia, a significant policy shift occurred with the issuance of Government Regulation No. 22 of 2021, which removed FABA from the category of hazardous and toxic waste (B3). This regulation aims to promote the use of FABA as a construction material and reduce pressure on landfill sites at power plants. However, the effectiveness of its implementation requires systemic planning and evidence-based policy modelling. One relevant approach for addressing the complexity of this issue is System Dynamics (SD). SD is a systems modelling method used to understand and simulate the behaviour of complex systems over time, considering interactions between elements, feedback loops, and time delays (Sterman, 2000).

The current condition at the Nagan Raya coal-fired power plant can be observed through the volume of FABA generated, as shown in **Figure 1**. Most of the FABA waste from this plant remains underutilized, highlighting a gap between production and utilization. Previous studies in Indonesia have primarily focused on technical-laboratory approaches or descriptive statistical analyses. Few have explicitly employed the System Dynamics method to evaluate integrated policy scenarios for FABA management. Based on these circumstances, this study aims to develop a policy simulation model for FABA utilization using the System Dynamics approach at the Nagan Raya power plant. This research is expected to provide a comprehensive understanding of waste management system dynamics and serve as a foundation for formulating adaptive, effective, and sustainability-oriented policies.

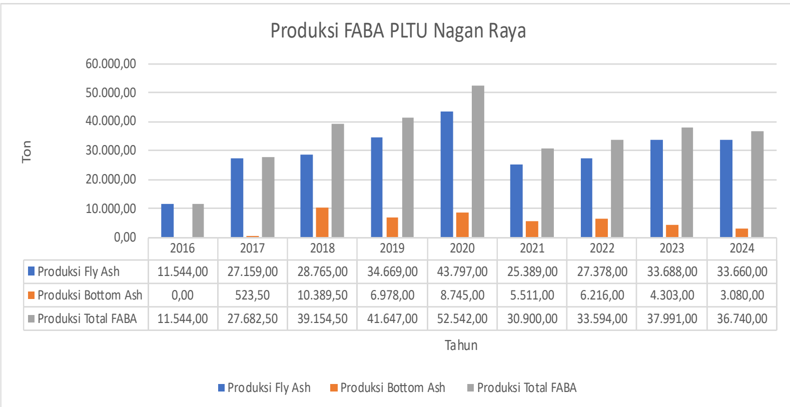

Figure 1 Annual FABA Production of Nagan Raya Coal-Fired Power Plant

2 Literature Review

This chapter discusses data and previous studies, as shown in **Table 1**, which serve as the basis for developing the FABA utilization model. The main focus is given to relevant references regarding the characteristics of FABA waste and industrial waste management policies, which are used to understand the dynamics of the system.

2.1 System Dynamics in FABA Management

The System Dynamics (SD) approach has been widely used to understand the behaviour of complex systems that involve interactions between components and changes over time. In the context of waste management, this approach is particularly useful as it is able to represent accumulative processes, decision making, as well as feedback from various policy variables. The SD model can illustrate how changes in one element, such as waste utilization rate, will affect waste stocks, operational costs, and market absorption capacity in the long run. Several previous studies have applied this approach to solid waste management systems, medical waste, as well as the energy sector. In the context of FABA waste, the dynamic systems approach is of high relevance given its system characteristics involving continuous flow of coal production process, waste accumulation, and inconstant utilization. FABA management includes aspects such as uncertainty in user demand, fluctuations in transportation and processing costs, and absorption capacity from sectors such as MSMEs and construction plants. Therefore, a model capable of simulating long-term policy scenarios in an integrated manner is needed. Until now, the use of a dynamic system approach to simulate FABA utilization policies specifically in PLTU is still very limited. Most of the existing research is still at the technical or static policy stage. Therefore, the development of dynamic models in this study not only contributes to the methodology of policy analysis but also enriches the literature on industrial waste management in the energy sector.

2.2 Previous Research

In the Table of Previous Research there have been several studies that discuss the provision of subsidies, tariffs, and penalties in reducing waste management problems, but none specifically on waste problems such as those that occur in this FABA case. This research utilizes a journal by Kuo et al. (2021) entitled “Toward a Circular Economy: A System Dynamic Model of Recycling Framework for Aseptic Paper Packaging Waste in Indonesia” as the main reference in developing a system dynamic model of FABA (Fly Ash and Bottom Ash) waste management. The journal made a significant contribution, especially in the application of the dynamic system approach to analyse incentive mechanisms in the form of recycling funds and subsidies in the context of extended producer responsibility (EPR). This approach proved to be able to evaluate the impact of financial policies on recycling rates, product circulation and waste accumulation. In the context of this study, Kuo et al.'s model provides a strong basic framework for building a FABA recycling system flow in Indonesia, including stakeholder engagement and simulation of various policy scenarios.

There are improvements made in this study. While Kuo et al.'s model focuses on paper-based aseptic packaging waste, this study expands the context to the solid waste of the power generation industry, namely FABA. In addition to the different types of waste, this study also developed a dynamic system network structure that includes specific variables such as collection costs, external costs, utilization by MSMEs and factories. With this approach, this study aims not only to maximize the utilization rate of FABA, but also to develop external subsidy-based policy scenarios that can accelerate the depreciation of accumulated waste stocks. Thus, while primarily referring to Kuo et al. (2021), this study develops a dynamic system model that is more contextual and relevant to FABA management conditions.

Table 1 Previous research on tariff policies and waste recycling

Authors	Model	Financial Systems	Results
Jia et al. (2017)	System dynamic	Penalty, Subsidy	Certain combinations of penalty and subsidy schemes can effectively address issues related to the management of construction and demolition waste
Bai et al. (2019)	PSM based nonlinear estimation method	R&D subsidy, Green Innovation	It may help to improve the efficiency of government R&D subsidies and promote the green innovation of energy-intensive firms.
Chang et al. (2019)	Game based, joint tax-subsidy mechanism	Tax, Subsidy	It shows a joint tax-subsidy mechanism can motivate the manufacturer to pursue eco-innovation and to incorporate the recycling considerations into its production and eco-innovation decisions.
Shih et al. (2019)	Recycling fund management model	Recycling fund, Subsidy rate	It suggests to utilize a differentiated rate and raise the fee to balance the long-term goals of fund management.
Wan and Hong (2019)	Optimal model	Recycling or remanufacturing subsidy, Price	The results show that the usage of either remanufacturing or recycling subsidy would stimulate the consumption, increase the recovery and improve the members' profits.
Li et al. (2020)	game based	deposit-refund	Current deposit-refund scheme can increase the collection rate of used EV batteries.
Kuo et al. (2021)	System Dynamics	EPR Tariff, Recycling Fund, Subsidies	The system dynamics model was used to simulate subsidy and recycling fund policies.

3 Research Methods

This section outlines the research methodology used to develop and simulate a system dynamics model for FABA (Fly Ash and Bottom Ash) utilization. The methodological framework includes problem identification, data collection, model construction, validation, and policy scenario simulation. A system dynamics approach is employed due to its ability to represent feedback loops, time delays, and complex interactions within the FABA supply chain system. Both quantitative and qualitative data are integrated to build a causal loop diagram and stock-flow model, which are used to analyze system behavior under various policy interventions.

3.1 System dynamics model development

Dynamic system models have been widely applied in various disciplines to understand the behaviour of complex systems holistically. However, its application in FABA management in the power sector is still limited. This research develops a dynamic system model to evaluate the impact of policies in the utilization of FABA, both in terms of technical material flow and management cost aspects. Model building is carried out based on actual conditions as shown in **Figure 2** FABA trade logistics network which divides into three main components: supply, distribution and consumer networks. Then proceed through the preparation of a causal loop diagram (CLD) to identify the relationship between variables, which is then derived into a stock and flow diagram (SFD) to formulate system dynamics. Data and parameters were collected through observation, PLTU operational reports, and previous literature. Model validation was conducted through comparison with actual data and sensitivity testing of key variables. Simulations were run to illustrate the system dynamics over a certain period, and were used to test policy scenarios such as subsidizing FABA utilization, changing utilization preferences, or adding beneficiary sectors. Simulation results are interpreted to evaluate the effectiveness of policies in reducing stored FABA stocks and increasing optimal utilization.

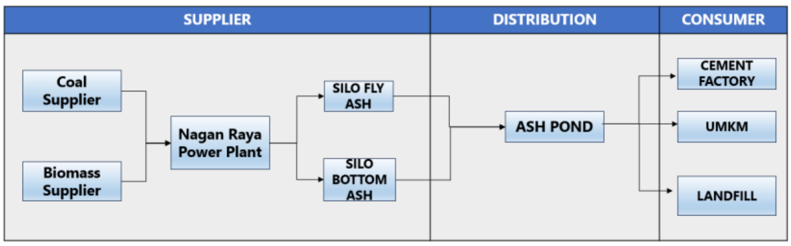

Figure 2 Trade Logistics Design of FABA

3.2 Causal Loop Diagram

Causal Loop Diagram (CLD) is used to illustrate the cause-and-effect relationship between variables in the Fly Ash and Bottom Ash (FABA) waste utilization system at PLTU Nagan Raya. This diagram shows how a change in one variable can affect other variables directly or indirectly, forming positive (reinforcing loop) or negative (balancing loop) feedback. The loops help in understanding the dynamics of complex systems and identifying relevant leverage points for policy improvements.

The causal loop shown in **Figure 3** explains first loop starts with electricity demand, which increases over time as a consequence of the growth rate. This demand drives an increase in electricity production, which in turn increases coal consumption through the coal flow variable. The amount of coal flow is also determined by the calorific value of coal and the proportion of energy mix such as biomass, as well as the conversion rate used in the system. An increase in coal consumption leads to an increase in the amount of FABA produced. The FABA produced then flows to the collecting flow, which is determined by the collecting rate. The collected FABA is temporarily stored in the FABA storage unit, before being utilized through the utilizing flow. The amount of utilizing flow is influenced by the community's demand for FABA, which is formed from the amount of interest (community FABA interest). This interest itself is influenced by the effectiveness of the socialization process and the dynamics of time. The utilized FABA is further classified based on the type of user, namely to industry (number of factory FABA), to micro, small and medium enterprises (number of UMKM FABA), and for special uses such as soil stabilization. Other loops in the system include collection and utilization cost flows, which result in total costs. This component includes collecting fees, collecting costs, as well as operational costs of each FABA user party such as MSME costs and factory costs. In addition, the model also accommodates internal stock changes by considering the amount of FABA removed from the system (the amount of FABA leaving), as an accumulation of all utilization pathways.

3.3 Stock and Flow Diagram

In modelling the FABA waste utilization system in this study, a dynamic system approach is used by applying a basic notation structure consisting of two main types of variables, namely stock (level) and flow (rate) as in **figure 4**. The stock variable describes the accumulative state in the system at a certain time, such as the amount of FABA stored and FABA utilized. Meanwhile, the flow variable describes the flow or change in value that enters or leaves the stock, such as collecting flow and utilizing flow, which indicates the volume of FABA collected and utilized in a certain unit of time. The model also contains various auxiliary variables and parameters that represent determining factors in the system, such as coal calories, coal conversion value, collecting rate, community FABA interest, to the number of factory FABA and the number of MSME FABA. Each relationship between variables is depicted in the form of causal links indicating a positive or negative causal relationship, depending on the direction of impact between variables.

The diagram structure shows three main stocks, namely FABA produced, FABA stored, and FABA utilized, which represent the journey of FABA waste from production to final utilization. The flow of FABA is controlled by two main flows, namely collecting flow and utilizing flow, which are influenced by the collecting rate and utilizing rate, respectively. The model facilitates analysis of the influence of changes in the electricity system and waste management on the dynamics of FABA utilization. In addition, the dynamics of electricity demand, which is influenced by demand growth and coal heating value, is the main driver of FABA production in the system. The mathematical equations corresponding to each variable are presented in **Table 2**

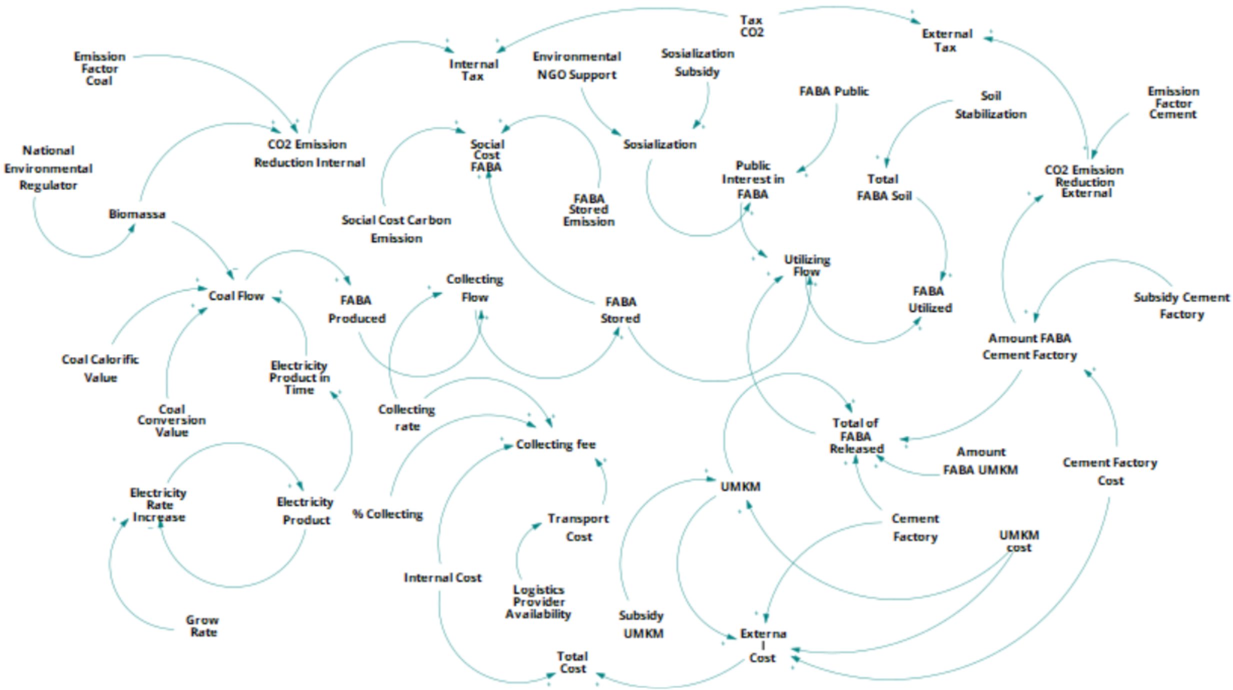

Figure 3 Detailed system dynamic model through the causal loop diagram.

3.4 System Dynamics Model Testing

The application of system structure and behavior was tested to ensure that the System Dynamics (SD) model can accurately simulate actual conditions. The test results indicate that the model is capable of replicating real-world conditions in terms of the relationship between electricity production and the amount of FABA stored can be observed in **Figure 5**. All key variables are included, and all dimensions are appropriate. The model boundaries are relatively relevant, and all model parameters have practical significance based on statistical regression analysis. The behavior fit test also showed that minor parameter variations did not lead to significant changes in model behavior or conclusions, indicating that the model has good validity. Furthermore, a simulation was conducted to compare the results with actual conditions based on historical data.

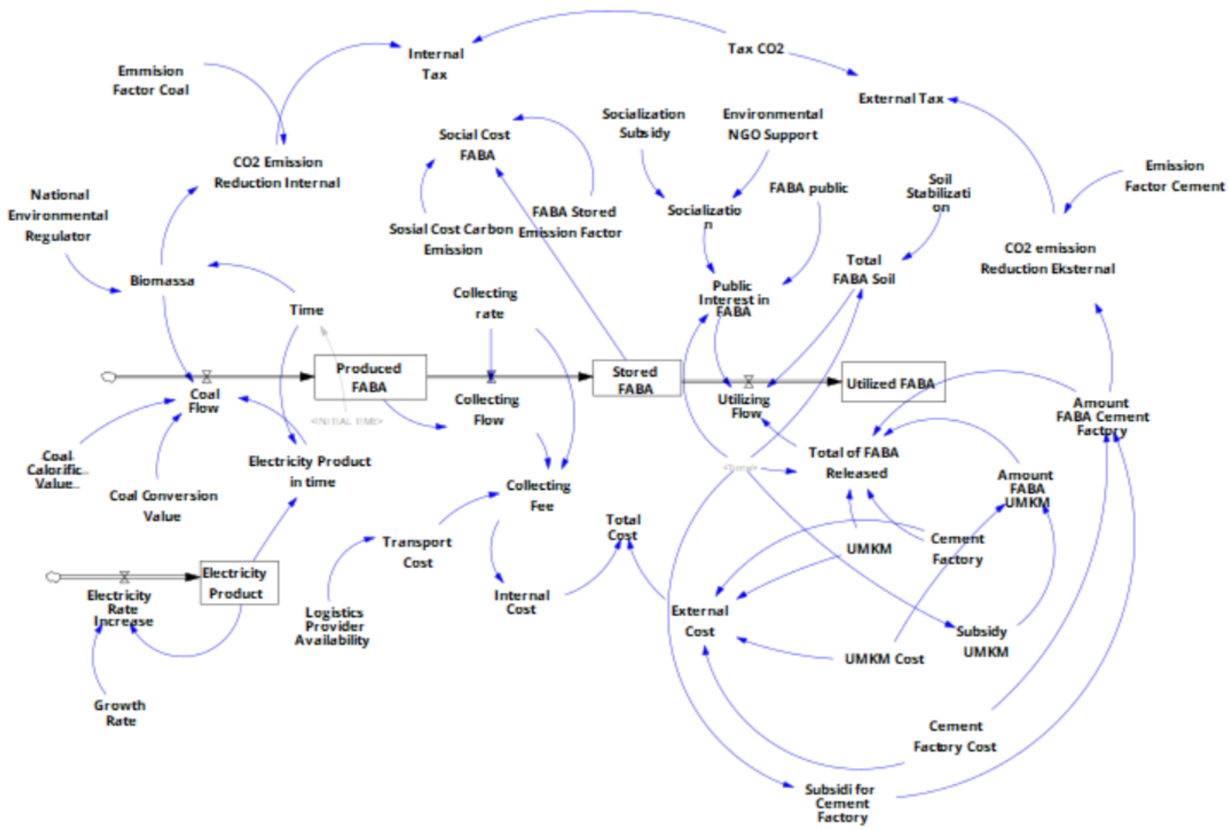

Figure 4 Stocks and flows of the proposed model

Table 2 Notations and mathematical formulation

Type	Component	Unit	Equations
Stok	Produced FABA	Ton	(Coal Flow*0.05) - Collecting Flow ; 0
Stok	Stored FABA	Ton	Collecting Flow-Utilizing Flow ;0
Stok	Utilized FABA	Ton	Utilizing Flow ; 0
Stok	Electricity Produced	KWH	IF THEN ELSE(Electricity Produced <120000, Electricity Rate Increase,0) ; 64953
Variable	Growth Rate	Dimensionless	0.007
Variable	Electricity Product in time	KWH/month	IF THEN ELSE(Time>108, 65000 , Electricity Product)
Variable	Coal Conversion Value	Dimensionless	0.75
Variable	Coal Calorific Value	Ton/KWH	3800
Variable	Biomass	Ton/month	500
Variable	CO2 Emission Reduction Internal	Ton/month	Biomassa*Emmision Factor Coal
Variable	Emission Factor Coal	Dimensionless	2.42
Variable	Internal Tax	IDR/month	Tax CO2*CO2 Emission Reduction Internal
Variable	CO2 Emission Reduction External	Ton/month	Amount FABA Cement Factory*Emission Factor Cement
Variabel	Emission Factor Cement	Dimensionless	0.9
Variable	External Tax	IDR/month	CO2 emission Reduction Eksternal*Tax CO2
Variable	Tax CO2	IDR/Ton	30000
Variable	FABA Stored Emission Factor	Dimensionless	0.02
Variable	Social Cost FABA	IDR/month	FABA Stored Emission Factor*Sosial Cost Carbon Emission*Stored FABA
Variable	Social Cost Carbon Emission	IDR/Ton	30000
Variable	Collecting Cost	IDR/Ton	70000
Variable	Collecting Fee	IDR/month	Collecting rate*Collecting Flow*Collecting cost
Variable	Collecting Rate	Dimensionless	0.98
Variable	Internal Cost	IDR/month	Collecting Fee
Variable	External Cost	IDR/month	Cement Factory*Cement Factory cost + UMKM*UMKM cost
Variable	Total Cost	IDR/month	Internal Cost + External Cost
Variable	Socialization	Dimensionless	Socialization Subsidy/20000000
Variable	Socialization Subsidy	IDR/month	0
Variable	FABA Public	Dimensionless	40
Variable	Public Interest of FABA	Dimensionless	IF THEN ELSE(Time>60, Interest Rate*Socialization , 0)
Variable	Soil Stabilization	IDR/month	10000
Variable	Total FABA Soil	IDR/month	IF THEN ELSE(Time>85:AND:Time<104, Soil Stabilization , 0)
Variable	Subsidy for Cement Factory	IDR/month	0
Variable	Amount FABA Cement Factory	Ton/month	400+IF THEN ELSE(Subsidy for Cement Factory >= 2*Cement Factory cost, 200 , 0)
Variable	Factory Cost	IDR/month	40000000
Variable	UMKM Cost	IDR/month	10000000
Variable	Subsidy UMKM	IDR/month	0
Variable	National Environmental Regulator	Dimensionless	0.1
Variable	Environmental NGO Support	Dimensionless	0
Variable	Logistics Provider Availability	Dimensionless	1
Variable	UMKM	Dimensionless	5 + IF THEN ELSE(Subsidy UMKM >= 2*UMKM cost, 5 , 0)
Variable	Factory	Dimensionless	2
Variable	Total of FABA Released		IF THEN ELSE(Time>60, Amount FABA Cement Factory*Factory +Amount FABA UMKM*UMKM,0)
Flow	Electricity Rate Increase	KWH/month	Electricity Product*Growth Rate
Flow	Coal Flow	Ton/month	(Electricity Product in time*Coal Conversion Value*Coal Calorific Value/4000)-Biomass
Flow	Collecting Flow	Ton/month	(Collecting rate*Produced FABA)
Flow	Utilizing Flow	Ton/month	(Total of FABA Released +Total FABA Soil)+Public Interest in FABA

4 Simulation Results and Case Study Discussion of FABA

This study develops a case study on the waste management system of FABA (Fly Ash and Bottom Ash) generated from coal combustion activities at the Nagan Raya coal-fired power plant (PLTU). The dynamic system network model employed includes various stakeholders involved, such as the power plant, ash pond, end-user industries, and PLN as the regulatory body responsible for setting subsidies

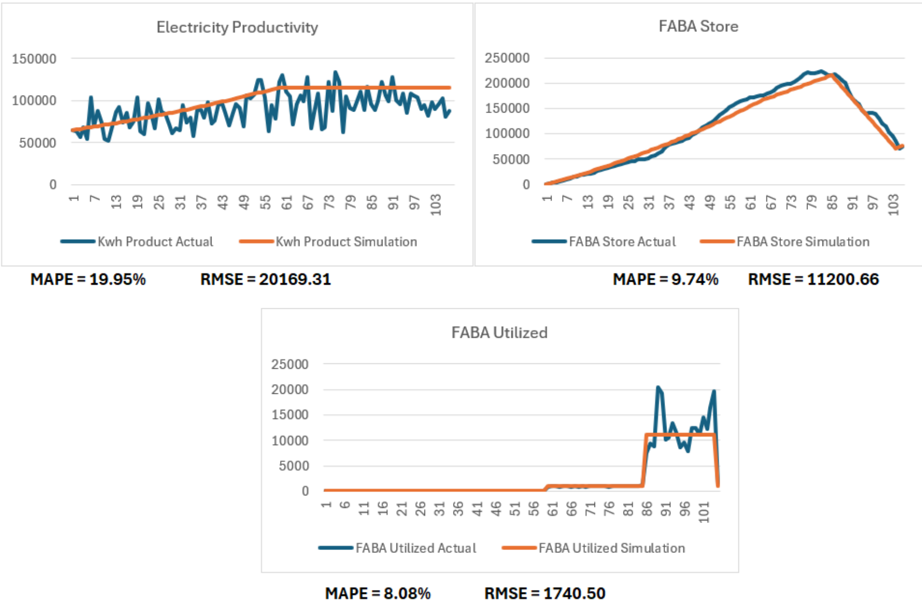

Figure 5 Comparison of Actual and Simulated Research Data

As part of behavioral validation, the model was tested by comparing the simulation results against actual historical data for three key variables: Electricity Productivity, FABA Store, and FABA Utilized. The primary objective of this test is to assess the extent to which the model can replicate the actual historical dynamics of the system. In general, a MAPE value below 20% indicates that the simulation results fall within an acceptable level of accuracy, as stated by Sterman (2000), who notes that model behavior need not exactly reproduce historical data, but should be able to replicate key trends and directions with reasonable accuracy to be considered valid. Therefore, based on this comparison, it can be concluded that the model has met the criteria for behavioral validation and is suitable for simulating FABA utilization policy scenarios.

To assess the model's sensitivity to parameter changes and its robustness under input uncertainty, a sensitivity and scenario analysis was conducted. Three key variables were selected: electricity growth rate (+100%), biomass substitution (-50%), and subsidies for user industries and public socialization (+100%). Each parameter was modified under extreme conditions to evaluate changes in system behavior, particularly with respect to key output variables: FABA Utilized, Stored FABA, CO_2 Emission Reduction, and Produced FABA.

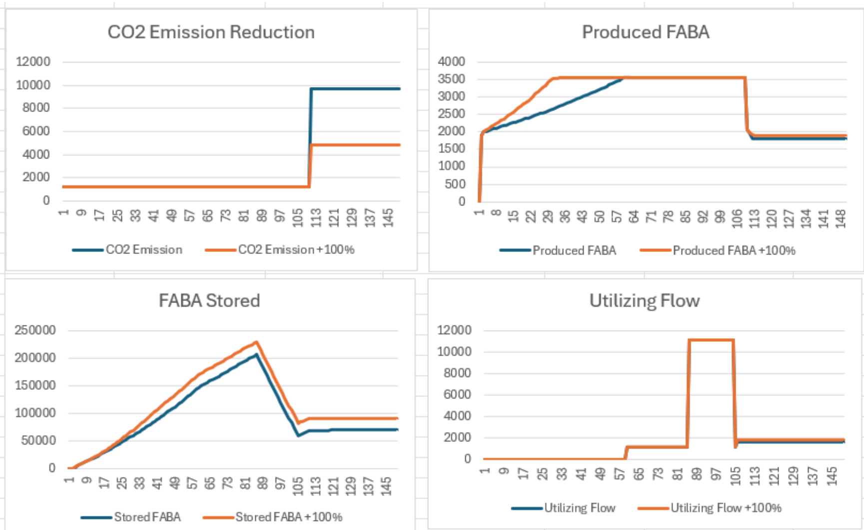

Figure 6 Sensitivity and Uncertainty Analysis

The model exhibited stable and interpretable behaviour under these extreme variations, confirming its robustness and policy relevance, and could be used in policy scenario simulations

4.1 Quantification of Key Variables

Primary data in this study were obtained from the Nagan Raya Coal-Fired Power Plant (PLTU), Aceh, as well as internal operational reports from PLN Nusantara Power (PLNNP) Nagan Raya as the operator of the power generation unit. The FABA management system examined includes total electricity production, the amount of FABA generated, the amount of FABA stored, and the total FABA utilized by user industries. Secondary data were obtained from literature studies, records, or other documents that served as references for the author in determining data quantification

4.2 Scenario Design

This study focuses on how to reduce the accumulation of FABA in the ash pond by increasing the FABA utilization rate through the provision of subsidies. To achieve this, several scenarios are developed, namely:

1. Biomass Addition Scenario

This scenario seeks to reduce the volume of FABA generated by applying co-firing technology, which involves the combined combustion of coal and biomass at the power plant. Since biomass has a lower ash content than coal, partially replacing coal with biomass leads to a direct reduction in FABA production. This initiative aligns with long-term emission reduction goals, targeting the broader implementation of biomass in coal-fired power plants. In the simulation, biomass input is increased to 4.000 tons to assess its impact on FABA generation.

2. Community Interest Enhancement Scenario

One of the major barriers to FABA utilization is the low public awareness of its economic value, such as its potential use in paving blocks, bricks, or cement substitutes. This scenario introduces a series of outreach programs, technical training, and product demonstrations aimed at raising public interest and participation. Within the model, this growing interest is represented by an increase in the number of educational campaigns, which positively influences the utilization rate of FABA.

3. User Industry Subsidy Scenario

This scenario focuses on providing financial incentives to industries that utilize FABA, such as cement manufacturers and small-scale enterprises. Subsidies are introduced to lower processing costs and encourage greater adoption of FABA as an alternative raw material. The policy aims to stimulate industrial demand and create a more favorable economic environment for sustainable waste utilization. Within the model, the subsidy is reflected as a factor that enhances the utilization rate through increased industry engagement.

4.3 Results and Discussions

A comprehensive simulation was conducted by integrating the three proposed scenarios biomass co-firing, public interest enhancement, and industrial subsidy to achieve maximum FABA utilization. **Figures 6** and **Figure 7** illustrate a comparison of the system conditions before and after the implementation of the scenarios. Figure 1 represents the baseline condition without any intervention, while Figure 2 presents the simulation results following the integrated application of the three scenarios. This comparison aims to assess the extent to which the policies influence the reduction of stored FABA stock and the overall improvement in utilization rates. The explanation of the values presented in the table will be provided in **Table 3**.

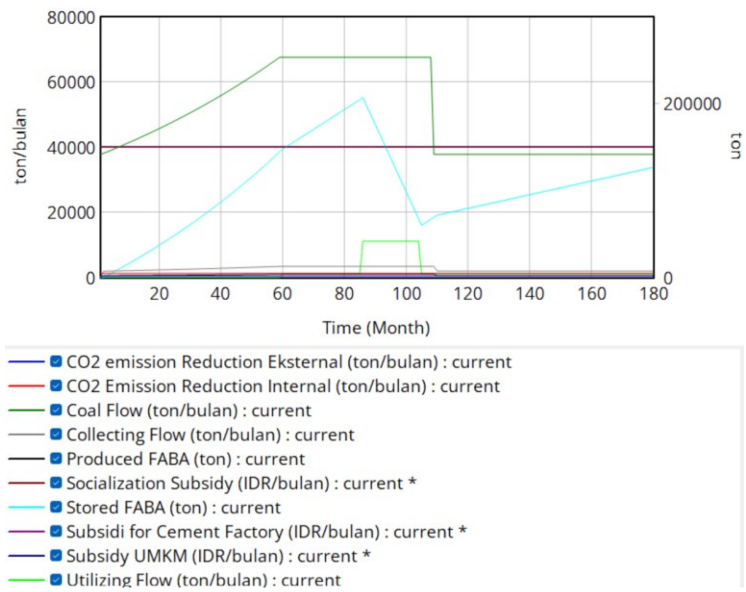

Figure 6 Simulation Results of FABA Conditions Before Scenario

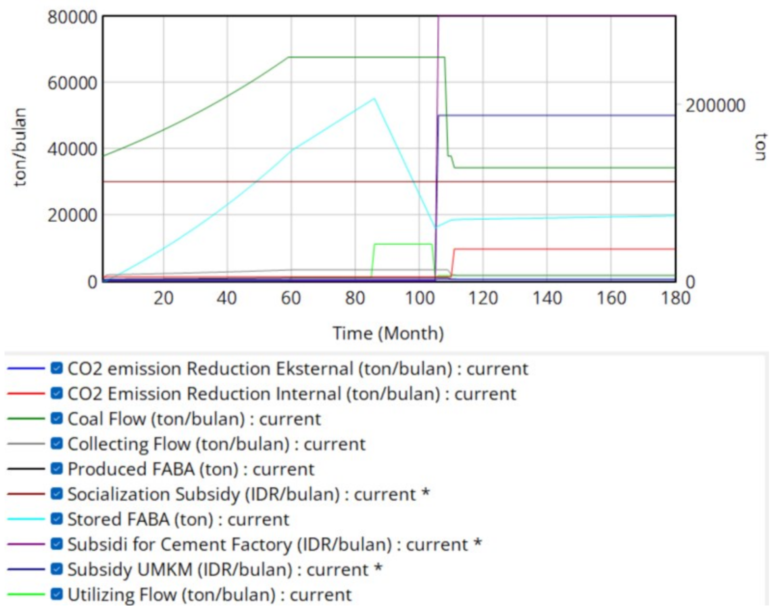

Figure 7 Simulation Results of FABA Conditions After Scenario

Tabel 3 Comparison of Simulation Results with Scenario Outcomes in 2030

	No Scenario	With Scenario	
Coal Flow	43607	40107	ton/month
Collecting Flow	2180	2005	ton/month
Utilizing Flow	1050	1850	ton/month
Produced FABA	2295	2110	ton
Stored FABA	98352	37011	ton
Biomass	500	4000	ton
Socialization cost	Rp0.00	Rp30.000.000,00	IDR/month
Consumer Subsidy	Rp0.00	Rp130.000.000,00	IDR/month
CO2 Emission Reduction	1570	10220	ton/month

5 Conclusions

This study has successfully developed a system dynamics model to analyze policy interventions aimed at increasing the utilization of Fly Ash and Bottom Ash (FABA) at the Nagan Raya coal-fired power plant. The simulation results indicate that the scenario involving direct subsidies to industrial actors (cement factories and MSMEs) has a significant impact on increasing the utilizing flow, which directly reduces the stored FABA stock. Meanwhile, the addition of biomass supports PLN's long-term goal of achieving net zero emissions while maintaining constant electricity production, although its contribution to FABA reduction is slower. The scenario aimed at increasing public interest yields moderate results and proves to be more effective when combined with continuous education and outreach strategies.

This study has several limitations, including the fact that the expected outcomes are not yet fully achieved, as FABA utilization has not significantly reduced the overall FABA stock. Therefore, additional scenarios need to be developed in the future. Moreover, the current model does not yet incorporate factors such as logistics distribution, FABA quality, FABA emission factors, and other relevant variables that could be addressed in future research

Declaration of AI Use

AI tools were used to assist with language editing, formatting consistency, and technical clarity. All content was reviewed and revised by the authors, who take full responsibility for the final version of this manuscript.

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