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Agriculture Biomass for Sustainable Electricity Supply Systems: A Dynamic System Approach

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Abstract

East Java has great potential in utilizing agricultural waste as a source of biomass energy to support the transition to New Renewable Energy (NRE). However, the development of biomass power plants faces challenges such as investment feasibility evaluation and biomass potential measurement. The East Java Government has set sustainable energy targets through Governor Regulations. This study developed a dynamic system-based simulation model to analyze factors influencing the utilization of agricultural waste as biomass energy. Verification results using Vensim PLE software show the model is valid with an error rate of E1 < 5% and E2 < 30%. In the Do-Nothing scenario, the electricity deficit could worsen in the future without increasing power plant capacity, especially from renewable energy. Conversely, the biomass power plant infrastructure development scenario shows that by 2024, the electricity deficit can be reduced from -7,599.47 GWh to -2,722.98 GWh. This trend continues in subsequent years, with the biomass scenario consistently decreasing the deficit and even generating a surplus in some years. Therefore, developing biomass-based power plants is a strategic step to reduce dependence on fossil fuels and enhance regional energy security in East Java.

Keyword: Agricultural Biomass, Dynamic Systems, Renewable Energy, Simulation Models

1. INTRODUCTION

East Java, as one of the largest agricultural producers in Indonesia, has great potential in utilizing agricultural waste as a renewable energy source [1]. The transition from fossil-based energy to new renewable energy has become a focus in the Regional Energy General Plan (RUED-P), but the implementation of biomass-based power plants in East Java still faces various challenges [2]. Dependence on fossil fuels, low utilization of agricultural waste, and limited renewable energy infrastructure are major obstacles [3]. Increasing the use of biomass electricity from agricultural waste will contribute to the diversification of electricity sources [4] and can reduce dependence on fossil fuels and strengthen regional energy security in East Java as a whole [3]. However, the increase in the use of agricultural biomass does not immediately provide instant results because it takes time for biomass-based electricity generation infrastructure to develop [5]. In addition, excessive growth in electricity production from agricultural biomass can put pressure on the agricultural sector due to the possibility of increased demand for agricultural waste [6]. Limitations in infrastructure and technology can also be obstacles to maximizing the potential of agricultural biomass-based electricity [7],[8]. This creates a complex cycle where increased use of agricultural biomass can trigger the growth of the new renewable energy sector, which in turn can provide incentives for the agricultural sector to produce more agricultural waste [9]. However, this increased demand must be balanced with consideration of agricultural production capacity which can lead to over-dependence [10].

Previous studies have revealed various issues related to renewable energy development. Duan et al. highlighted that investment in wind and solar power in the China-Pakistan Economic Corridor (CPEC) has not been sufficient to meet policy targets due to lack of electrification and unclear planning, thus exacerbating the energy crisis [11]. Bamooeifard found that wind energy development is hampered by the risks and dynamic costs of short-term remedial actions, which makes it less profitable [12]. Quantara & Suryani stated that the use of new renewable energy faces obstacles in providing electricity in remote areas, especially islands far from electricity generation sources [13]. Sunitiyoso, et al. used a systems approach to analyze the renewable energy electricity sector and found that system complexity can hinder target achievement [9]. Ahmad & Tahar emphasized that delays in planning and construction are major barriers to the transition from fossil fuels to renewable energy [14]. According to Mana et.al, Agricultural biomass-based electricity generation has great potential in various countries. In Morocco, biomass can supply clean electricity to 254,252 households [15]. Souza et al argue that while Brazil stands out in the use of agricultural and forestry residues for energy [16]. Bharti et al. argue that GIS-based analysis can optimize the use of agricultural waste as fuel [17]. Mixing biomass with coal can also reduce GHG emissions significantly [18]. Kosovo has 4.57 million tonnes of biomass per year, with 74.6% suitable for energy use [19]. while the European Union can utilize 15% of agricultural biomass for energy needs [20]. Utilization of wood and other biomass residues can increase energy security, reduce global warming, and generate electricity and heat efficiently [21], [22]. In Tanzania, biomass waste residues have the potential to support small-scale electricity generation through diesel generators and anaerobic digestion [23]. These studies confirm that careful planning and policy support are essential for sustainable renewable energy development.

Biomass has great potential as a renewable energy source due to its abundance and positive environmental impacts, but effective models to analyze the energy potential of agricultural waste are still limited. In contrast to previous studies, this research uniquely focuses on the dynamic system approach to analyze the utilization of agricultural waste for biomass energy in East Java. Differences from previous study, that may focus on static models or different regions, this approach provides a comprehensive simulation that considers the specific conditions of East Java. Based on these problems, this study aims to develop a dynamic system simulation model to overcome these challenges. This model is designed to explore how agricultural waste can be optimally utilized to meet electricity needs in East Java. This study contributes by introducing a dynamic system approach to analyze the utilization of agricultural waste as biomass energy in East Java. This approach allows a more comprehensive understanding of the long-term impacts and potential of biomass energy by considering the conditions of a particular region. Through this approach, this study is expected to support the diversification of sustainable energy sources, accelerate the transition to new renewable energy, and strengthen energy security in East Java.

2. MATERIALS AND METHOD

This section describes the stages carried out in developing a simulation model to meet electricity needs through the utilization of Agriculture Biomass with a Dynamic System approach. This model aims to support the fulfillment of electricity needs while increasing the utilization of New and Renewable Energy (NRE). The research method used in this study is divided into three parts which will be explained in Figure 1.

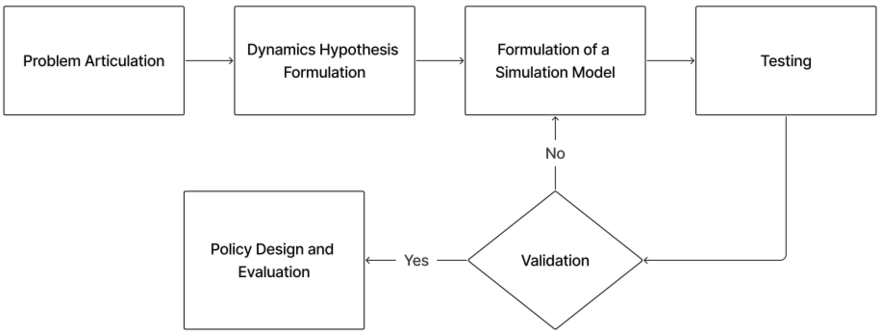

Figure 1. Research Methodology

2.1. Problem Articulation

East Java Province faces major challenges in meeting sustainable electricity needs amidst the transition from fossil fuels to NRE. One potential solution is the utilization of agricultural waste as a source of biomass energy, considering that East Java has a large agricultural waste production. However, there are several challenges, such as dependence on fossils, minimal NRE contribution due to lack of infrastructure, and suboptimal utilization of agricultural waste. This study aims to develop a dynamic system simulation model to analyze the utilization of agricultural waste in meeting electricity needs and supporting sustainable energy diversification in East Java. The historical data used covers the period 2000-2022, while the simulation horizon covers the period 2023-2035. The data for this study were sourced from PT. PLN, Ministry of Energy and Mineral Resources, East Java Agriculture Service, and Central Statistics Agency records from 2000 to 2022. Variables were selected based on their relevance to biomass energy production and their impact on the energy system, justified through a review of existing literature and expert consultations.

2.2. Dynamics Hypothesis Formulation

In formulating the dynamics hypothesis for the utilization of agricultural biomass in meeting electricity demand, several key assumptions and relationships need to be established based on the identified system variables. This section presents the hypotheses related to the dynamics of agricultural biomass utilization in the context of electricity generation.

1. Hypothesis on Agricultural Waste Production and Biomass Power Generation
   The first key hypothesis is that an increase in agricultural waste production will positively influence the potential for biomass power generation [24]. As the availability of agricultural waste rises, it will provide a more substantial feedstock for biomass power plants [25]. This relationship assumes that the necessary infrastructure is in place to convert agricultural waste into usable energy. Thus, a higher production of agricultural waste directly contributes to the ability to generate more electricity from biomass sources.

2. Hypothesis on Agricultural Productivity and Biomass Feedstock Supply
   Another hypothesis involves the relationship between agricultural productivity and the supply of biomass feedstock. Increased agricultural productivity leads to more agricultural waste being produced, which can then be utilized in biomass power generation [26]. Furthermore, higher agricultural output may incentivize farmers to expand their agricultural land, further increasing the supply of waste available for biomass energy production [27]. This positive feedback loop can continuously support the growth of the biomass energy sector.

2.3. Formulation of a Simulation Model

The conceptual model is developed into a formal model that includes equations and parameters to ensure the system is represented accurately [28]. This model is presented in the form of a causal loop diagram, with each variable included in the Figure 2. The Causal Loop Diagram (CLD) has a dynamic structure that is depicted using icons and arrows that are directly connected to the existing differential equations [29].

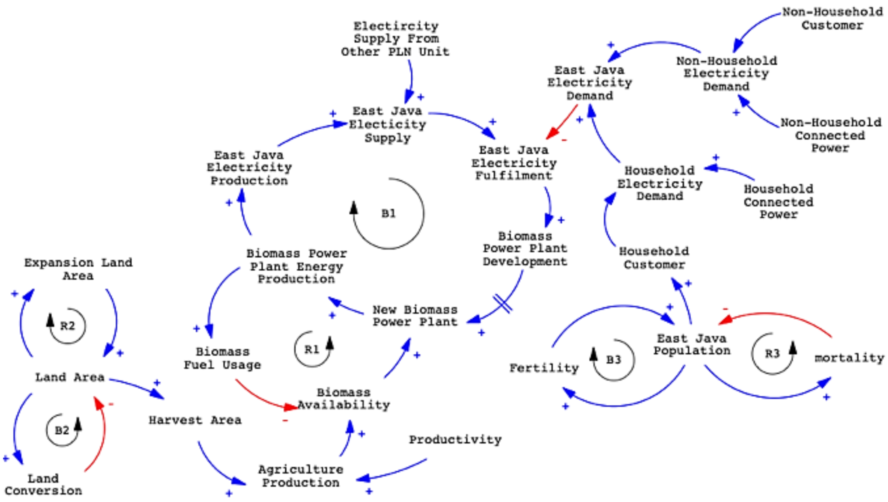

Figure 2. Causal Loop Diagram (CLD)

2.4. Testing

This validation involves checking the error rate and error variance. The model is considered valid if the error rate (E1) is less than 5% and the error variance (E2) is less than 30%. According to sources, system validation involves comparing the mean value and the amplitude variation (error variance). If both of these conditions are met, the model is considered valid [28], [29], [30]. Model validation as shown in Equations (1) and (2).

$$E1 = \frac{|\bar{S} - \bar{A}|}{\bar{A}} \quad (1)$$

$$E2 = \frac{|S_S - S_a|}{S_a} \quad (2)$$

Where $\bar{S}$ is the mean of the simulated data, $\bar{A}$ is the mean of the historical data, S_s is the standard deviation of the simulated data, and S_a is the standard deviation of the historical data. Behavior Reproduction testing is conducted to validate the model's ability to reproduce real system behavior based on historical data. This validation involves checking the error rate (E1) and error variance (E2) as indicators of model accuracy. A model is considered valid if it meets the following two main criteria:

1. Error Rate (E1) is the percentage of the average difference between the model output and historical data. The model is considered valid if the E1 value is less than 5%, indicating that the simulation results are close to the actual values with minimal deviation.
2. Error Variance (E2) measures the extent to which the model simulation results are consistent with the variability of historical data. The model is valid if the E2 value is less than 30%, indicating that the model can represent the system fluctuation pattern well.

The Behavior Reproduction validation process is carried out by comparing the results of the model simulation with relevant historical data, such as electricity production data or agricultural waste utilization. The model output is analyzed using statistical methods to calculate E1 and E2. If both criteria are met, the model is considered to have good validity and can represent the dynamics of the actual system. This validity indicates the extent to which the model can be used as a tool for analysis and decision-making. With a low error rate, the model provides confidence that the relationships between variables and the resulting system behavior reflect reality. This allows the model to be used reliably in scenario development and strategic planning based on dynamic systems.

2.5. Policy Design and Evaluation

In this section, two scenarios will be analyzed to evaluate future energy management policies. The first scenario is the Do-Nothing scenario, where there is no change in the energy resource management policy or other power generation supply. In this scenario, there is no attempt to introduce new technologies or policies to increase the use of renewable energy, and the electricity system remains dependent on existing fossil fuel sources. The main focus of this scenario is to analyze how the development of limited biomass power plants or even no policy changes can affect the total electricity supply and the fulfillment of electricity needs in the future. The second scenario is the development of biomass power generation infrastructure, which aims to reduce dependence on fossil fuel sources.

In this scenario, biomass power plants are developed in stages by considering the potential of available biomass resources, as well as the infrastructure and technology needed. By comparing the two scenarios, insights can be gained into the potential benefits and challenges of developing biomass-based renewable energy in the future.

3. RESULTS AND DISCUSSION

3.1. Model Structure Testing Result

Model structure testing aims to ensure that the developed model reflects a logical and consistent relationship with the basic principles of biomass-based energy systems. This verification process includes an evaluation of the suitability of the relationship between variables in the model to ensure that the dynamics of the system described are in accordance with reality. In addition, dimension testing is carried out to check the consistency of units in each variable, to ensure that the calculations in the model are carried out accurately. This testing was carried out using Vensim PLE software, by utilizing the Check Model and Check Unit features. Based on the test results, Figure 3. and Figure 4. can be concluded that the developed stock and flow diagram (SFD) model has been well validated, both in terms of the logic of the relationship between variables and the consistency of units in each variable in the model.

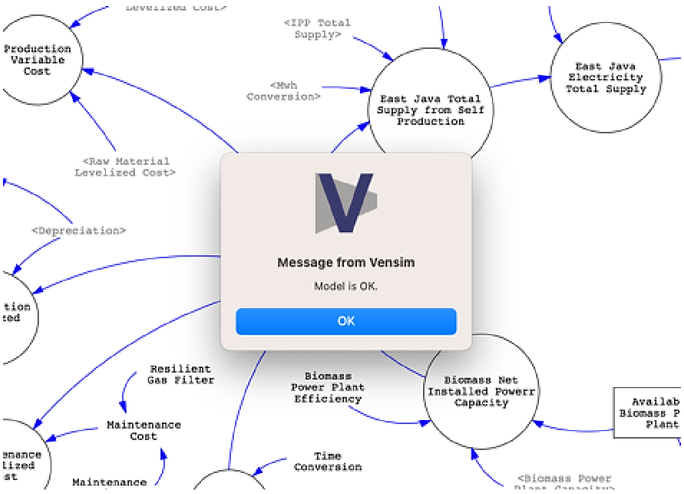

Figure 3. Result of Model Testing

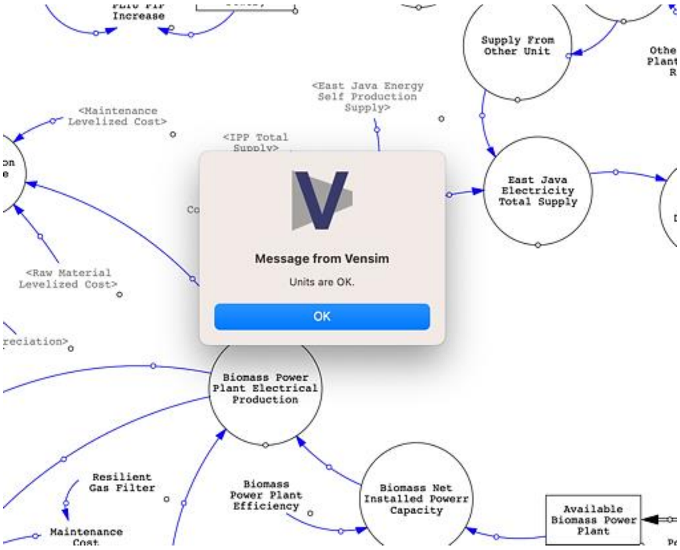

Figure 4. Result of Unit Testing

3.2. Base Model

Figure 5. shows the development of electricity demand fulfillment in East Java from 2000 to 2022. In this model, negative values indicate a shortage of electricity supply, while positive values indicate a surplus or more than sufficient fulfillment. During the period 2000 to 2009, the data shows a significant imbalance between electricity demand and fulfillment, with several years such as 2003 and 2009 experiencing large deficits, above -3500 GW. However, in 2012, there was a positive spike reaching more than 3300 GW, indicating an increase in fulfillment. After 2012, fluctuations in electricity fulfillment are more varied, with surpluses in several years such as 2016 and 2017, but shortages also still occur in several years after that, such as 2020 which showed a deficit of more than -4000 GW. Overall, this model describes an unstable dependence on electricity supply in East Java, with fluctuations reflecting dynamics in energy management and distribution during the period.

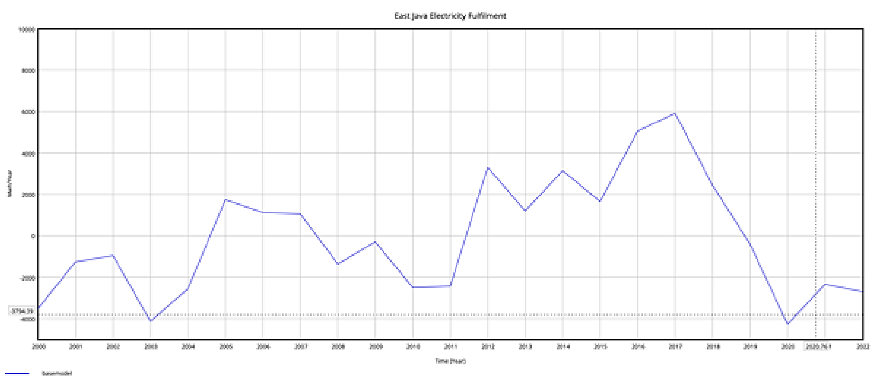

Figure 5. Base Model Result

3.3. Model Behavior Testing Result

Model behavior testing aims to ensure that the developed model can represent the real behavior of key variables related to the existing sub-system, throughout the specified time. In this test, further analysis is carried out on each variable to assess the extent to which the model can reflect the actual conditions. The validity of the test is determined using two parameters: E1 and E2. The test is considered valid if the value of E1 is less than 5% and E2 is less than 30%. Table 1. shows that the model can be relied on to represent the dynamics of the biomass-based energy system with an adequate level of accuracy. Thus, the results of this test ensure that the model can be used to predict the behavior of the energy system over a specified time.

Table 1. Results of Error Rate and Error Variance Validation

Time	Total Production		Distribution Usage		Electricity Demand	
	Actual	Simulation	Actual	Simulation	Actual	Simulation
2000	14,945.12	13,585.60	13,703.86	12,532.70	15,700.64	16,044.40
2001	15,997.83	15,166.60	14,138.71	13,991.10	16,343.96	15,265.00

Time	Total Production		Distribution Usage		Electricity Demand	
	Actual	Simulation	Actual	Simulation	Actual	Simulation
2002	16,803.38	17,040.20	14,907.11	15,719.50	17,020.18	16,713.30
2003	17,649.64	15,053.40	15,558.07	13,886.70	17,319.45	18,083.60
2004	18,535.01	17,385.50	16,684.21	16,038.10	17,635.71	18,672.50
2005	19,468.06	20,004.70	17,836.36	18,454.30	17,969.92	16,786.90
2006	20,054.79	21,377.80	18,385.47	19,721.00	18,323.10	18,545.50
2007	21,163.35	21,805.40	19,511.89	20,115.50	19,467.44	19,223.60
2008	21,871.98	21,706.60	20,291.73	20,024.30	20,334.39	21,075.30
2009	22,765.21	23,053.10	21,245.52	21,266.50	21,058.20	22,006.80
2010	24,120.94	22,931.00	22,439.54	21,153.80	22,469.54	22,332.70
2011	26,151.72	23,831.50	24,220.02	21,984.60	24,018.69	25,667.80
2012	28,824.50	29,677.60	27,132.82	27,778.20	26,910.18	26,219.60
2013	30,687.91	29,465.10	28,693.11	27,579.30	28,708.11	27,698.60
2014	32,525.10	32,932.60	30,523.99	30,824.90	30,523.98	29,630.00
2015	32,951.19	32,887.00	30,824.81	30,782.20	30,824.81	28,331.30
2016	35,081.70	35,765.80	32,926.84	33,476.80	32,926.84	29,003.50
2017	36,142.61	36,361.80	34,114.15	34,034.60	34,114.16	30,309.60
2018	37,863.94	37,296.30	35,427.38	34,909.40	35,817.90	32,702.40
2019	39,406.79	38,637.70	36,825.13	36,164.90	37,228.94	37,104.60
2020	39,610.23	40,069.20	37,089.03	37,504.80	37,613.55	40,788.80
2021	41,629.70	41,480.10	38,919.52	38,825.40	39,457.19	41,338.20
2022	43,062.40	42,893.20	40,019.76	40,148.00	40,546.87	41,613.70
Average	27,709.27	27,409.03	25,713.87	25,518.11	26,188.42	25,876.42
Standard Deviation	8,956.17	9,208.48	8,610.47	8,729.26	8,286.30	8,266.92
E1	1.08%		0.76%		1.19%	
E2	2.82%		1.38%		0.23%	

3.4. Scenario Result

3.4.1 Do-Nothing Scenario

This scenario is used to understand the extent of the decline in electricity fulfillment if no new power plants are built in the future. By simulating this condition, the model can estimate the gap between electricity demand and supply due to increasing electricity needs, for example from population growth, urbanization, and industrialization, while the capacity of existing power plants tends to decline due to age, decreasing efficiency. The simulation results can show how much electricity needs are not met.

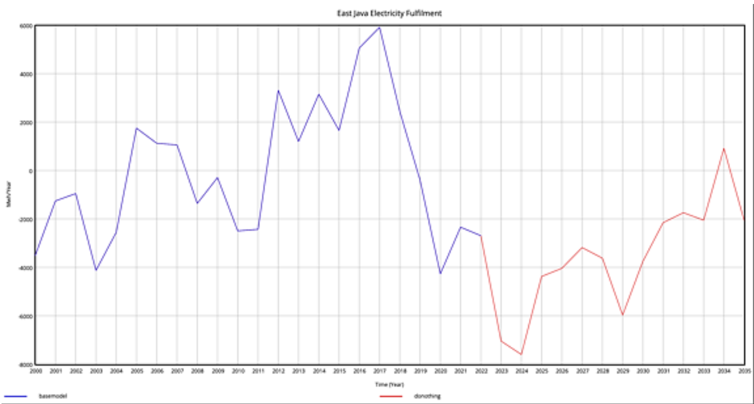

Figure 6. Result of Do-Nothing Scenario

Figure 6. Shows, the comparison results between the base model and the do-nothing scenario show that both models have identical behavior throughout the observed period, with the same figures for the East Java Electricity Fulfilment variable for each year from 2000 to 2022. In the do-nothing scenario, which assumes no policy changes or development of power generation infrastructure, the fulfillment of electricity needs in East Java is expected to continue to experience shortages. Without increasing power generation capacity, especially from renewable energy, negative electricity fulfillment could be even greater in the future. This indicates the inability of the system to meet the increasing electricity demand, potentially reducing the quality of electricity fulfillment, and having an impact on various sectors. Therefore, interventions such as the development of renewable energy-based power plants are needed to ensure sustainable electricity fulfillment in the future.

3.4.2 Biomass Power Plant Infrastructure Development Scenario

In this section, biomass power plants will be developed to offset the dependence on fossil fuels without any changes in policy or other supply conditions in the model. In this scenario, the main focus is on how the expanded biomass power plants can affect the total supply and electricity fulfilment in the future.

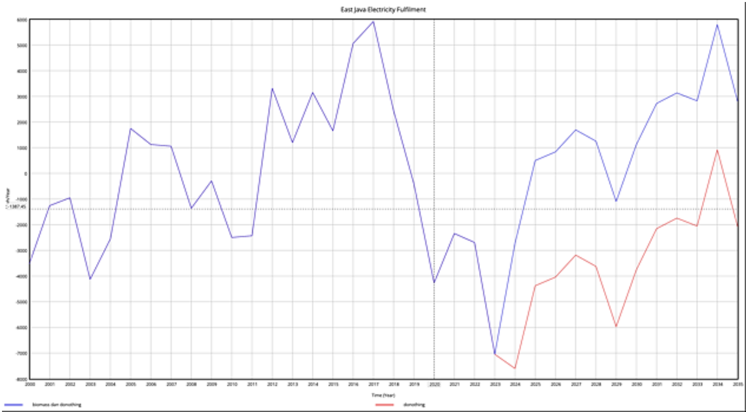

Figure 7. Result of the Biomass Power Plant Infrastructure Development Scenario and the Do-Nothing Scenario

Figure 7. shows that the development of biomass power plant infrastructure has a significant impact on meeting electricity needs in East Java when compared to the Do-Nothing scenario. In 2024, the electricity fulfillment deficit in the biomass scenario was recorded at -2,722.98 GWh, much lower than the deficit of -7,599.47 GWh in the do-nothing scenario. This means that the contribution of biomass succeeded in reducing the deficit by 4,876.49 GWh in that year. This trend continues in the following years, with the biomass scenario showing a consistent reduction in the deficit. For example, in 2030, the biomass scenario recorded a surplus of 1,123.63 GWh, while the do-nothing scenario still showed a deficit of -3,752.86 GWh. In 2035, the biomass scenario recorded a surplus of 2,812.93 GWh, while the do nothing scenario was still at a deficit of -2,063.56 GWh. The data can be seen more specifically in the following Table 2.

Table 2. Data of the Biomass Power Plant Infrastructure Development Scenario and the Do-Nothing Scenario

Time (Year)	Biomass dan Donothing	Donothing
2000	-3511.74	-3511.74
2001	-1256.82	-1256.82
2002	-952.737	-952.737
2003	-4126.73	-4126.73
2004	-2554.66	-2554.66
2005	1747.19	1747.19
2006	1123.67	1123.67
2007	1056.24	1056.24
2008	-1359.34	-1359.34
2009	-293.745	-293.745
2010	-2497.24	-2497.24
2011	-2429.46	-2429.46
2012	3310.97	3310.97
2013	1199.12	1199.12
2014	3148.99	3148.99
2015	1653.28	1653.28
2016	5057.77	5057.77
2017	5913.43	5913.43
2018	2435.97	2435.97
2019	-401.629	-401.629
2020	-4267.46	-4267.46
2021	-2341.67	-2341.67
2022	-2692.11	-2692.11
2023	-7045.12	-7045.12
2024	-2452.07	-7599.47
2025	771.427	-4375.97
2026	1106.81	-4040.59
2027	1964.02	-3183.38
2028	1526.01	-3621.39

Time (Year)	Biomass dan Donothing	Donothing
2029	-823.479	-5970.88
2030	1394.54	-3752.86
2031	2994.53	-2152.87
2032	3403.14	-1744.26
2033	3095.32	-2052.08
2034	6062.11	914.711
2035	3083.85	-2063.56

Figure 8. shows a comparison of the total electricity supply in East Java between scenarios that include the development of biomass power plants (biomass and do-nothing) with a do-nothing scenario without additional power plant intervention. Until 2022, both scenarios show the same electricity supply figure, which is 42,893.2 GWh. However, after 2022, there is a significant difference.

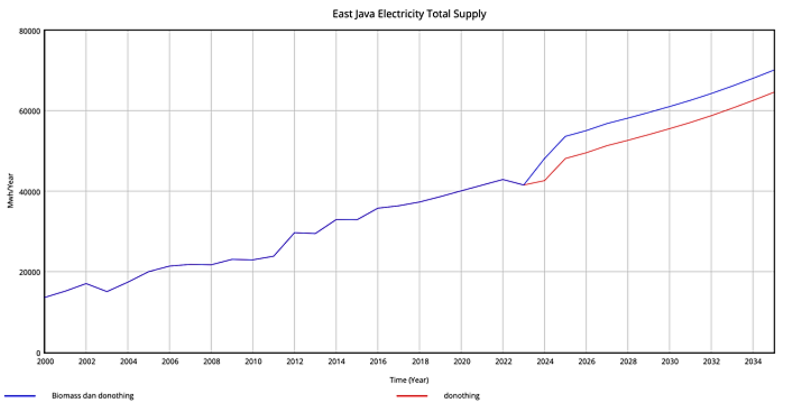

Figure 8. Result of Total Supply

The Biomass scenario shows a rapid increase in total electricity supply, reaching 70,037.2 GWh in 2035. This indicates that biomass development can substantially increase electricity supply capacity. The Do-Nothing scenario, despite increasing due to the development of existing capacity, only reaches 64,537.8 GWh in 2035, with a slower growth rate than the biomass scenario. The significant increase in the biomass scenario shows the important role of biomass power generation in meeting electricity demand, reducing supply gaps, and supporting energy source diversification.

3.5. Discussion

The results of this study indicate that the utilization of agricultural waste as a source of biomass energy has great potential to support sustainable energy transition in East Java. This finding is in line with previous studies showing that biomass can reduce dependence on fossil fuels and improve regional energy security [3], [4]. However, this study also revealed several challenges that need to be overcome to maximize the potential of biomass. One of the main implications of this research is the reduction of carbon emissions. Biomass has the potential to be a carbon-neutral energy source [3], [4], [11], since the carbon released during biomass combustion is comparable to the carbon absorbed by plants during photosynthesis [5], [26]. In addition, the use of biomass can increase energy efficiency by utilizing previously unused agricultural waste [15], [27]. The economic benefits of biomass systems are also significant, including job creation in the agricultural and energy sectors, as well as increased incomes for farmers [3], [18].

However, this research also has limitations. Technical challenges such as low energy conversion efficiency and high investment costs are still major obstacles [5], [7], [8]. In addition, the potential for negative environmental impacts such as deforestation and soil degradation need to be considered. Dependence on specific infrastructure is also a constraint, especially in rural areas that may not have access to the necessary technology and facilities [9], [11]. The developed model may not be fully applicable to other regions without adjustments, because each region has specific conditions such as the availability of agricultural waste, energy needs, and different infrastructure. In addition, this study has not included transportation costs and other costs related to fuel, so a more in-depth supply chain analysis is needed. This study has also not conducted an in-depth analysis of the environmental impacts of biomass power plants, including life cycle analysis and environmental risks such as fire and pollution. Therefore, further research is needed to adjust the model to the specific conditions of other regions, evaluate transportation and logistics costs, and assess environmental impacts comprehensively.

The practical implications of the results of this study include the potential for implementation in developing countries such as Indonesia, especially in East Java. This study brings an innovative approach by utilizing agricultural waste as a renewable energy source, which will significantly increase the New Renewable Energy (NRE) mix in East Java Province. Efforts to use agricultural waste as an energy source make a positive contribution to environmental protection. By reducing agricultural waste, this study also plays a role in mitigating climate change, which is by global demands to protect the earth's environment.

4. CONCLUSION

This study shows that the utilization of agricultural waste as a source of biomass energy has great potential to support sustainable energy transition in East Java. The developed dynamic system-based simulation model is valid and reliable to predict the behavior of the energy system over a certain time. The simulation results show that without intervention, the electricity deficit will increase significantly. However, with the development of biomass power generation infrastructure, this deficit can be reduced substantially, even producing an electricity surplus in the future. Therefore, the development of biomass-based power generation is a strategic step to reduce dependence on fossil fuels and improve regional energy security. The main contribution of this study is to show that biomass can reduce dependence on fossil fuels, improve regional energy security, and potentially reduce carbon emissions. The use of biomass can also improve energy efficiency by utilizing previously unused agricultural waste, as well as provide economic benefits such as job creation and increased income for farmers. For further research, it is recommended to explore the application of biomass technology in various geographic regions with different specific conditions, as well as develop more efficient and sustainable biomass conversion technologies. In addition, further research is needed to evaluate transportation and logistics costs, as well as assess environmental impacts comprehensively through life cycle analysis and environmental risk analysis. Thus, the developed model can provide a more comprehensive picture of the efficiency and economic sustainability of biomass power plants.

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