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System Dynamics-Based Industrial Modeling of Aluminium Processing in Indonesia

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Abstract. The Indonesian aluminum industry has great potential due to its abundant bauxite reserves, but downstream development to increase added value is still limited. This study uses a dynamic system model to simulate the development of Indonesia's aluminum industry, taking into account variables such as bauxite reserves, production capacity, demand, energy costs, raw material prices, and downstream development barriers. A scenario-based simulation method is applied to evaluate the impact of various policies, including import substitution, increased production capacity, and the use of coal-fired electricity in aluminum smelting plants. The simulation results show that the optimal scenario produces total emissions of 158,276 tons of CO_2eq, total profits of USD 48,321.60 million, and energy consumption of 22,075,800 MWh, which is more efficient than other scenarios. The contribution of this research lies in providing a technical framework for dynamic system modeling to support more measurable and sustainable downstream aluminum industry strategy planning.

Keywords: System dynamics, industrial process modeling, aluminum production, feedback loop, simulation model.

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1. Introduction

The development of the aluminum industry in Indonesia has a significant impact on economic growth, community welfare, and national defense strategies. This industry not only supports economic growth through job creation, but also plays a strategic role in national infrastructure and technology development. However, despite increases in production and employment, the sector faces a number of technical and operational challenges, including production efficiency, labor replacement, uncontrolled urban growth, and significant environmental impacts [1]. Diversification of strategies and supply security are crucial to reducing dependence on primary resources and increasing industrial independence [1].

On the demand side, global and national aluminum demand shows a high growth trend. In 2020, Indonesia's demand reached 1 million tons, while domestic production only reached 250 thousand tons, resulting in aluminum imports reaching 748 thousand tons. The potential for developing Indonesia's aluminum industry is quite large, considering that the country has the fourth largest bauxite reserves in the world, namely around 1.2 billion tons of metal, with total bauxite ore resources reaching 6.2 billion tons [1]. Bauxite, which consists of aluminum (Al), oxygen (O), and hydrogen (H) in the form of hydroxide (OH), is the main raw material in the upstream industry, which is then processed into alumina (Al_2O_3) and aluminum in a reduction smelting plant with a production ratio of 4:2:1 [1]. Based on forecasts using the ARDL and VAR methods through MAPE validation, Indonesia's bauxite demand for the 2020–2025 period is estimated to reach 18,616,342 tons [2].

To support bauxite downstreaming, the Indonesian government has issued Law No. 3 of 2020 concerning the prohibition of mineral ore exports and a long-term strategy for mineral management through the Ministry of Energy and Mineral Resources. With this policy, domestic aluminum production is expected to increase to 8.0 million tons per year by 2045. However, increasing production capacity poses technical challenges, such as smelting process optimization, energy efficiency, and environmental impact reduction [3]-[5].

Previous studies have emphasized the importance of technological innovation in the aluminum industry [6]. In Europe, the aluminum industry has developed sustainability indicators to monitor industry progress and trends, while demonstrating a commitment to continuous improvement, although environmental impacts, particularly greenhouse gas emissions from energy consumption, remain a concern [7]. The use of low-carbon technologies, renewable energy sources, and efficient production methods such as Bayer-hydroelectric has been shown to reduce environmental impact while providing economic benefits [8]-[10]. Dynamic system-based simulation studies show that combining electrolysis technology innovation and hydropower utilization is an effective strategy for the long-term development of a low-carbon aluminum industry [11].

In addition, other studies in the context of downstreaming metal industries such as copper and nickel in Indonesia show that a dynamic systems approach can increase industrial added value and strengthen the national economy, while analyzing the impact of policies on environmental sustainability [12]-[14]. An analysis of the performance of the aluminum industry in Yogyakarta confirms that this industry is still in its early stages of maturity, so product life cycle-based strategies and market trends need to be applied to extend the industry's life cycle [15].

Demand for aluminum in strategic sectors, such as Dirgantara Indonesia, which has not been fully met, has driven the need to import aluminum in the form of plates, rods, and sheets [16]. Efforts to increase production capacity have also been made at PT. Indonesia Asahan Aluminum (Persero), with a target of increasing smelter production to 300,000 TPY to meet domestic and international demand [17].

Although there has been a lot of research related to the development of the aluminum industry, there are still significant research gaps. Studies using a dynamic systems approach to simulate the integrated development of the aluminum industry are still limited. In addition, research related to sustainable diversification strategies, optimization of resource use, and analysis of the socio-economic impact of the aluminum industry, including corporate social responsibility for community welfare, still needs to be expanded [18] [19]. This study aims to fill these gaps by emphasizing the analysis of economic impact, added value enhancement, and dynamic system simulation-based technical strategies, as applied to the Hall-Heroult process for electrolytic aluminum production [20] [21].

The results of this study are expected to contribute significantly to the development of the aluminum industry in Indonesia, both technically and economically. Specifically, this study can provide recommendations related to production optimization, energy efficiency, and bauxite downstreaming strategies to increase the added value of the industry. In addition, this study is also expected to support the formulation of sustainable policies, reduce environmental impacts, and improve the welfare of communities surrounding the aluminum industry.

2. **Methods**

This research method uses a dynamical systems modeling approach to comprehensively examine the development of the aluminum processing industry in Indonesia, from upstream to downstream.

2.1 Research Stages

Based on Figure 1 below, this study began with a literature review to understand theories and findings related to the aluminum industry, followed by the identification of problems from upstream to downstream and the formulation of research objectives. Data collection was carried out from various sources, including production, consumption, exports and imports, technology, policies, and economic, social, and environmental impacts. The data was used to build a dynamic system model using Cause and Effect Diagrams (CED) and Stock and Flow Diagrams (SFD), which were then verified and refined according to actual conditions. The final stage involved policy scenario analysis through simulation to assess the impact on the economy, labor, and carbon emissions, resulting in the best policy strategy for the sustainable development of the aluminum industry in Indonesia.

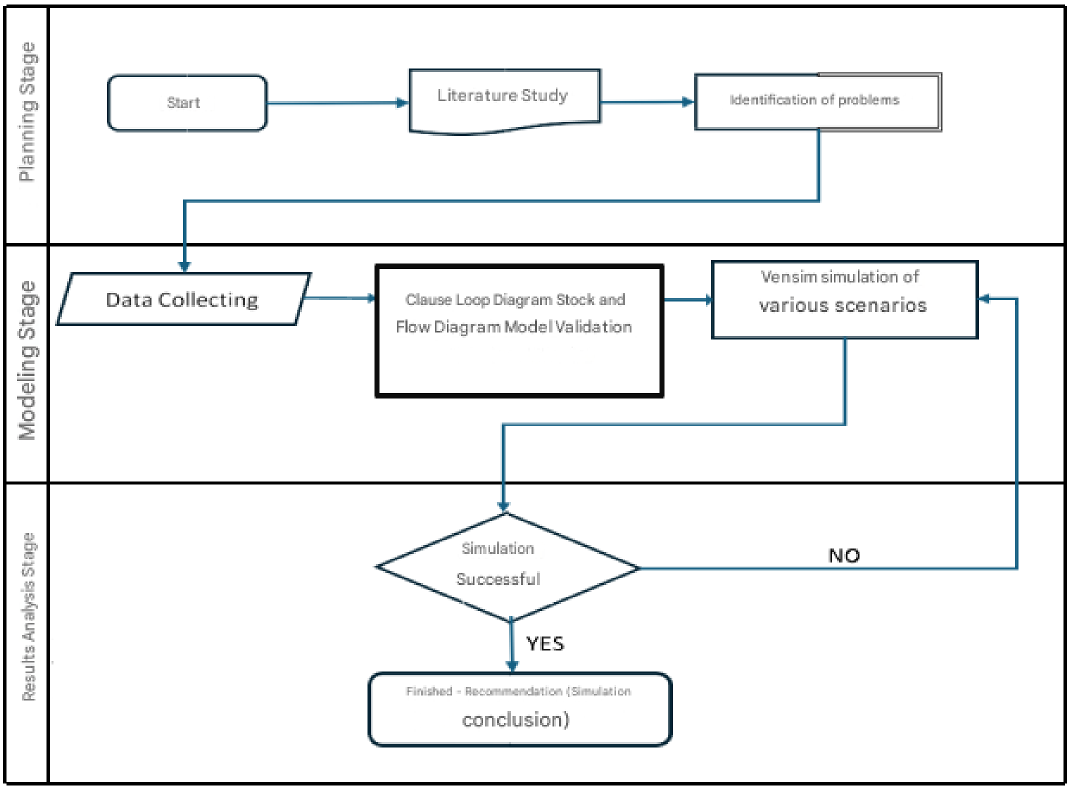


Figure 1. Research Stages

2.2 Research Location

This study focuses on the aluminum industry in Indonesia as the study location. The selection of Indonesia is based on the large potential of bauxite resources, the national downstreaming program, and the challenges faced in developing the aluminum industry, both in terms of production, technology, and policy. Data were obtained from various related agencies and industry players to build a dynamic system model that represents national conditions as a whole.

2.3 Data Collection and Acquisition

The data needed to be collected for this research includes:

1. Production and Trade Data: Data on bauxite, alumina, and aluminum production in Indonesia, as well as export and import data for these products.

2. Capacity and Infrastructure Data: Data on aluminum smelter capacity, energy availability, and other supporting infrastructure.
3. Environmental Impact Data: Data related to the environmental impacts of bauxite mining and aluminium processing, such as emissions, water usage and waste generation.
4. Economic Data: Data related to global aluminum prices, production costs, and other economic factors affecting the industry.
5. Projected data on economic growth and future aluminum demand.

Data sources will include various official institutions such as the Ministry of Energy and Mineral Resources (ESDM), BPS (Central Bureau of Statistics) and Kemenperin (Ministry of Industry), as well as secondary sources such as scientific publications and industry reports. All data was converted into numerical variables for stock and flow modeling with consistent units, so that it could be input into simulation software, as shown in Table 1 below.

Table 1. Bauxite, Alumina & Aluminum Stock Data

Year	Bauxite (in K.Ton)		
	Production	**Import**	**Export**
2012	15.915.2	6.7	29.506.5
2013	57.000	8.8	57.023.7
2014	2.560	4	2.085.4
2015	472	13.3	-
2016	1.400	11.05	-
2017	2.900	5.1	1.714.6
2018	2.693.6	13	8.650.1
2019	16.592.1	15.3	15.500.1
2020	25.859.8	14.5	19.422.1
2021	25.781.1	10.7	19.914.4
2022	28.808.6	15.5	17.845.1
Year	**Alumina (in K.Ton)**		
	Production	**Import**	**Export**
2012	-	518.4	0,002
2013	-	516.1	0,485
2014	-	569.9	0,12
2015	70	514.2	19.3
2016	470	509.4	421.4
2017	990	399.9	967.9
2018	950	439.9	947.7
2019	1.100	435.8	1.080.6
2020	960	399.5	907.8
2021	1.360	359.9	1.292.6
2022	-	329.8	2.024.1
Year	**Aluminium (in K.Ton)**		
	Production	**Import**	**Export**
2012	253	881.3	307.6
2013	255.3	772.7	301.9
2014	264.5	498.8	213.1
2015	257.1	542.7	168.7
2016	245	625.1	111.2

2017	218.7	727.7	137.8
2018	219.3	595.7	185.7
2019	249.5	539.3	143.2
2020	245.1	384.4	336.1
2021	200.6	546.5	245.2
2022	223.7	486.7	261.2

2.4 Data Analysis and Tools

After data collection, an analysis was conducted using a dynamic system approach to produce a simulation model related to the development of the Indonesian aluminum industry. The simulation model to be run is based on a conceptual model that has been verified using Vensim. In addition, research data quantification will be carried out, namely by entering mathematical equations and entering units of each variable into the stock and flow diagram. The dynamic system model has a causal relationship called Causal loop.

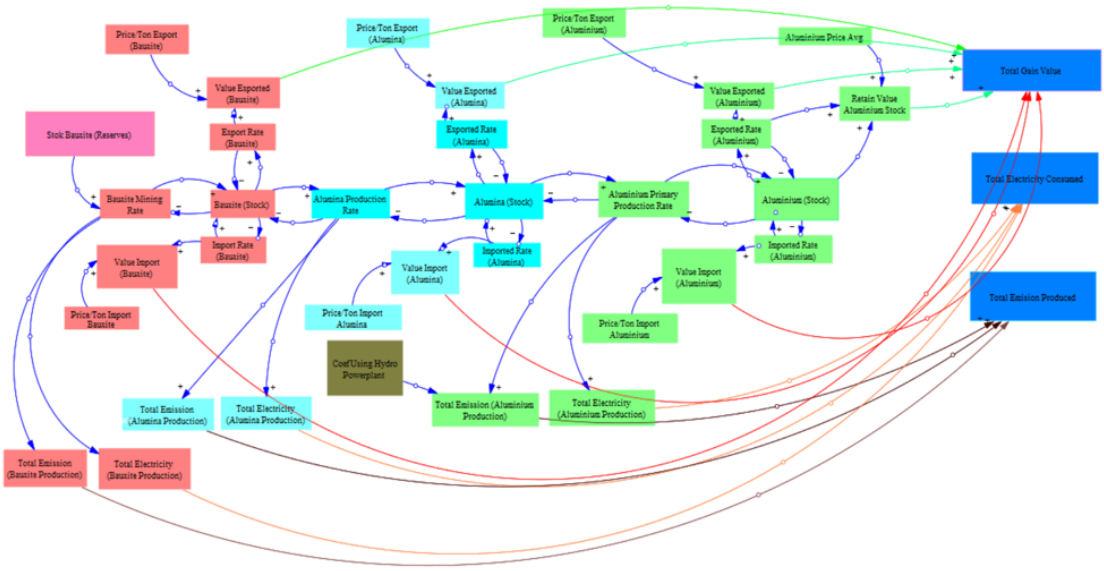


Figure 2. CLD (Causal Loop Diagram)

Stock and Flow Diagram (SFD) is built to quantify the dynamics of the aluminum downstream system by emphasizing changes in stocks and material flows and their relationship to energy and emissions. In this diagram, stockmain includes Bauxite Stock, Bauxite (Stock), Alumina (Stock), and Aluminum (Stock).

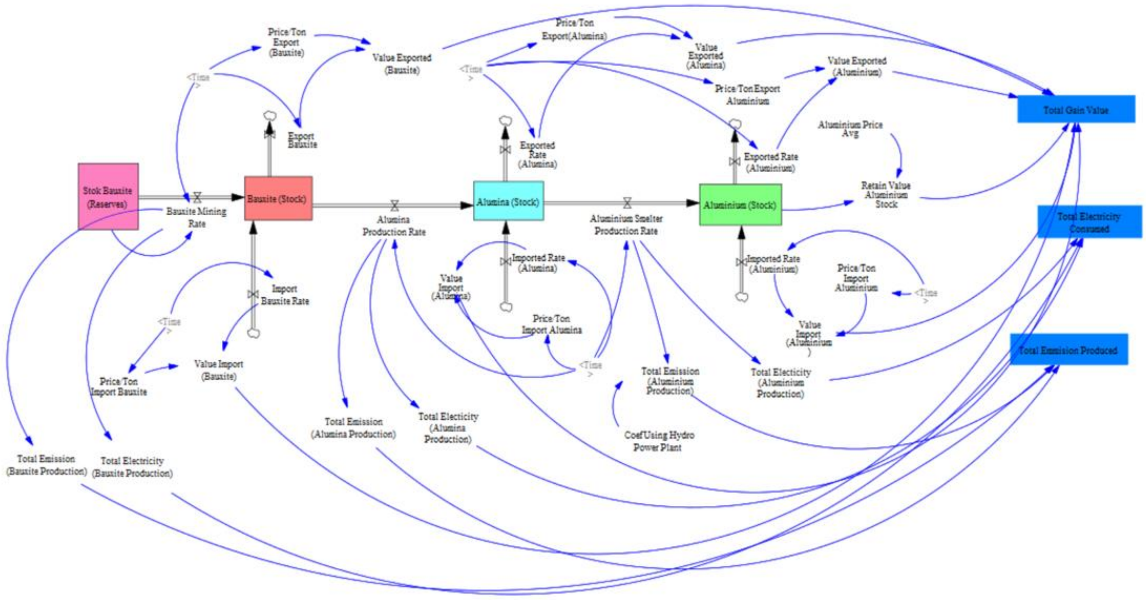


Figure 3. SFD (Stock and Flow Diagram)

2.5 Model Validation

Model validation testing was carried out using the approach Mean Absolute Percentage Error (MAPE) to measure the level of accuracy between the results of the model simulation and actual data. The results of the validation test based on Lewis (1992) show the MAPE value into 4 categories, including if the MAPE value <10% is categorized as very accurate, 10-20% is in the good category, 20-50% is in the fair category and MAPE> 50% is inaccurate, so in this study the author determined that the error limit must be less than 10% so that the simulation results can represent the system in the aluminum industry quite well.

Table 2 Validation Test Results Using MAPE

No	Variables	MAP	Conclusion
1	Bauxite Proposal	0,42 %	<10% is acceptable
2	Bauxite Mining	5,72 %	<10% is acceptable
3	Alumina Production	0,25 %	<10% is acceptable
4	Aluminum Production	0,11 %	<10% is acceptable

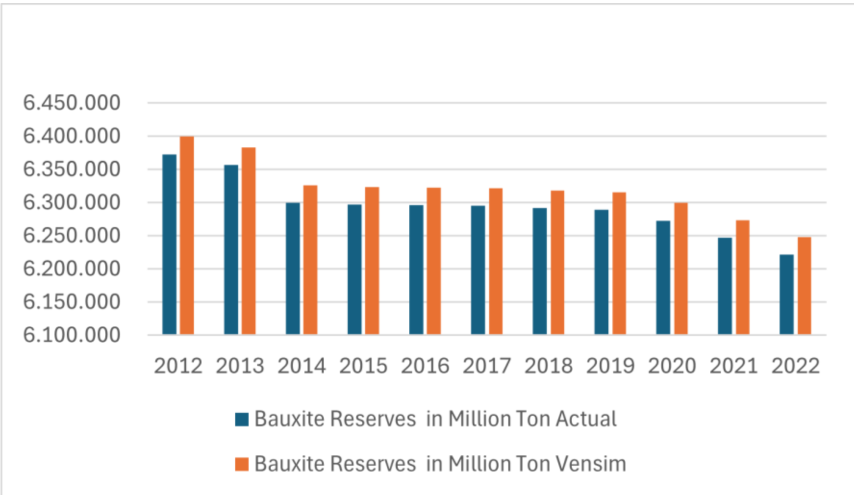


Figure 4. MAPE Validation of Bauxite Reserves

In figure 4. the graph shows the downward trend in bauxite reserves from year to year. The blue bars (Actual) and orange bars (Vensim) are almost indistinguishable, confirming that the simulation model successfully replicates the dynamics of the decline in bauxite reserves very well. The accuracy of this model is reinforced by a MAPE value of 0.42%.

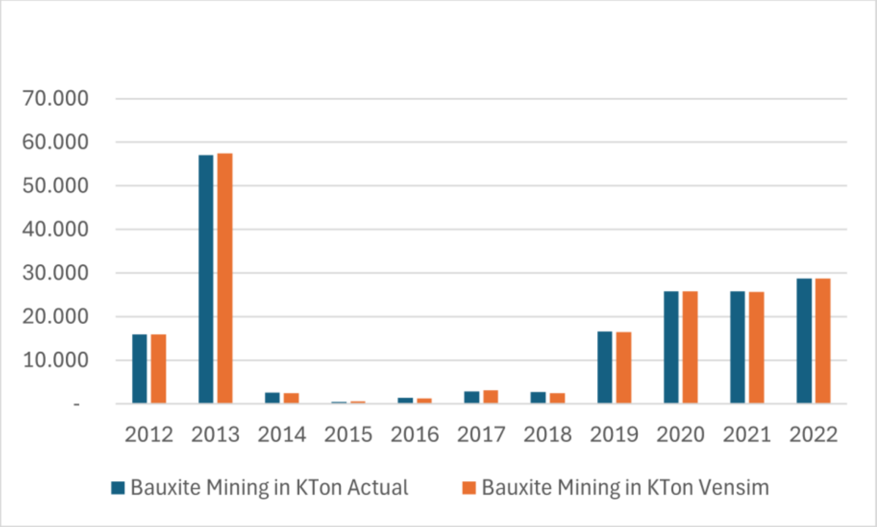


Figure 5. Bauxite Mining MAPE Validation

The graph in Figure 5 shows significant fluctuations in bauxite mining activity, particularly the surge in 2013 and subsequent years. Nevertheless, the Vensim model (orange bars) successfully tracks the actual data (blue bars) very well. This similarity indicates that the model has a good ability to simulate bauxite mining, with a MAPE value of 5.72%, which is still in the "highly accurate" category.

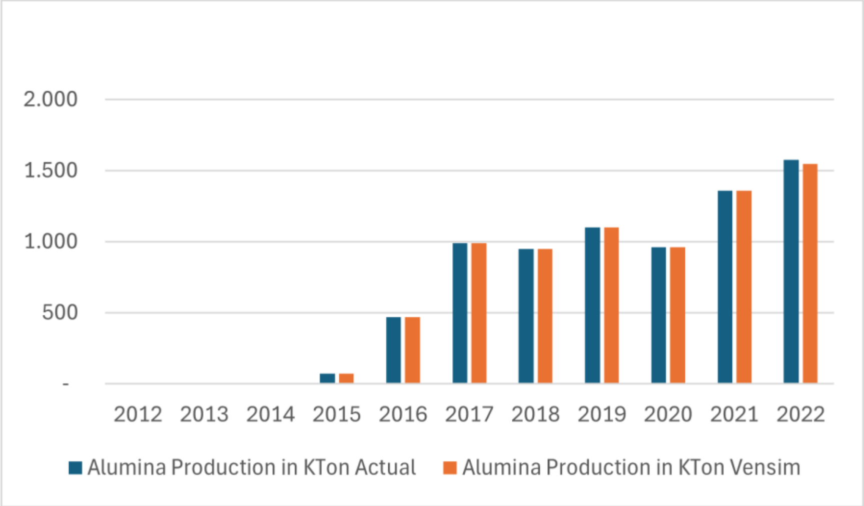


Figure 6. Alumina MAPE Validation

The graph in Figure 6 shows a significant increase in alumina production from 2015. The blue bars (Actual) and orange bars (Vensim) again show remarkable similarity, especially in years with high production. This proves that the Vensim model is highly accurate in modeling alumina production, supported by a MAPE value of 0.25%.

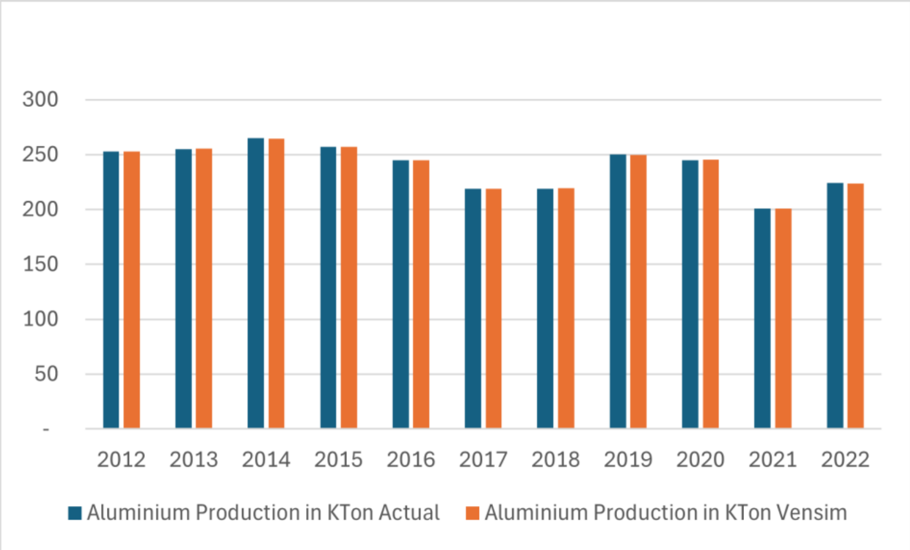


Figure 7. Aluminum MAPE Validation

In Figure 7, the blue bar (Actual) and orange bar (Vensim) show very similar values for each year. This indicates that the Vensim simulation model is very accurate in predicting aluminum production. This conformity is supported by a very low MAPE value of 0.11%, indicating exceptional accuracy.

3. Results and Discussion

Model Scenario I

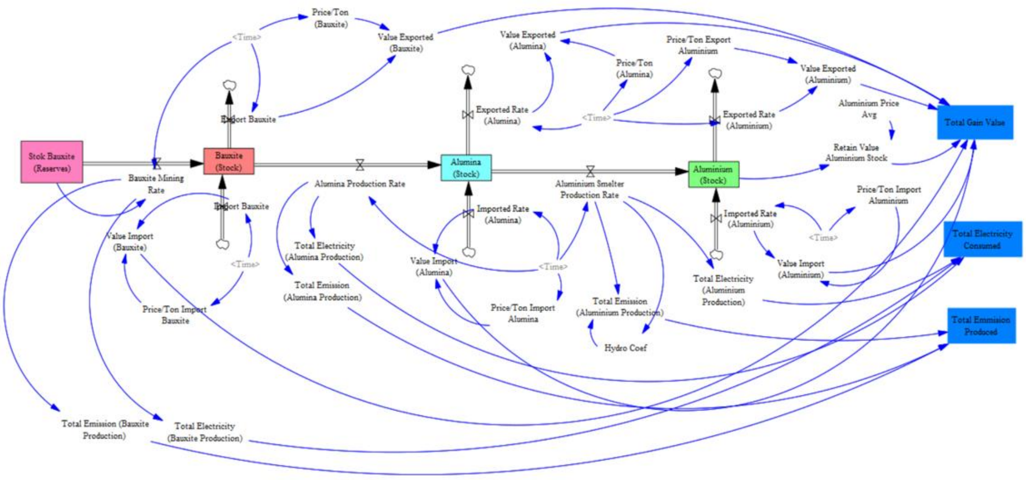


Figure 8. SFD Model-Scenario I

Results of Vensim Simulation Model Scenario I

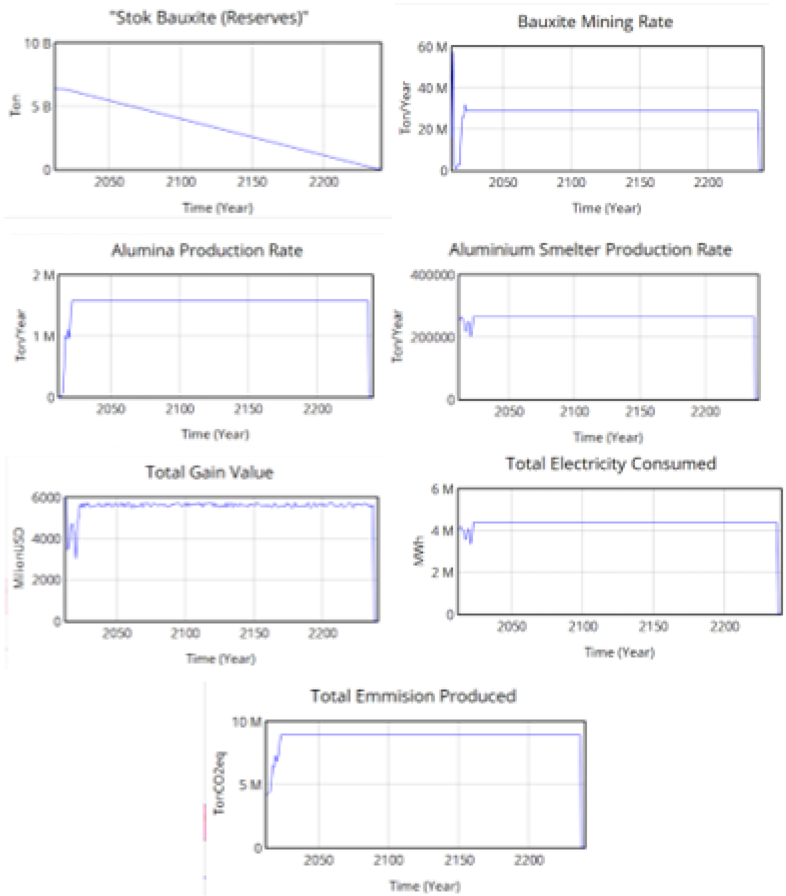


Figure 9. Results of Vensim Simulation Model Scenario I

Model Scenario II

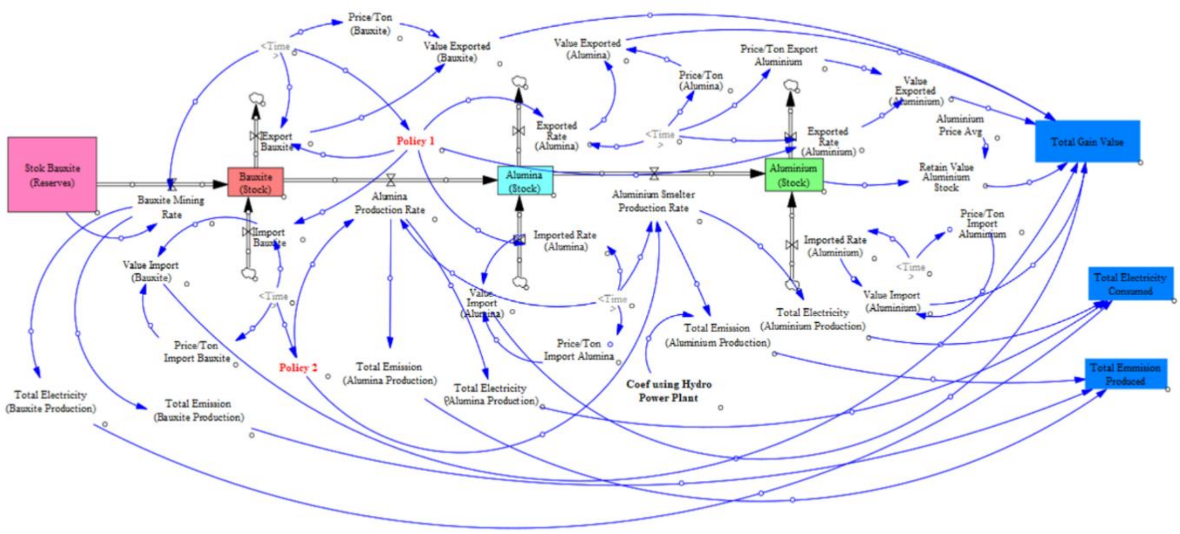
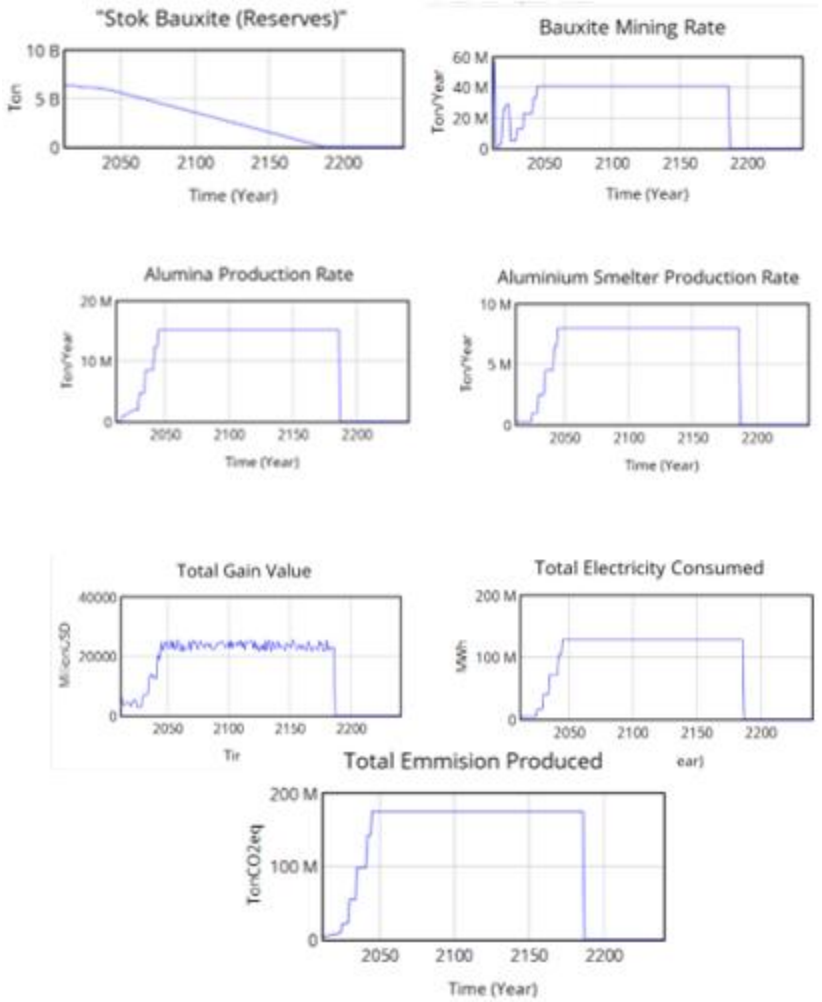


Figure 10. SFD Model-Scenario II

Results of Vensim Simulation Model Scenario II



Fiureg 11. Results of Vensim Simulation Model Scenario II

Model Scenario III

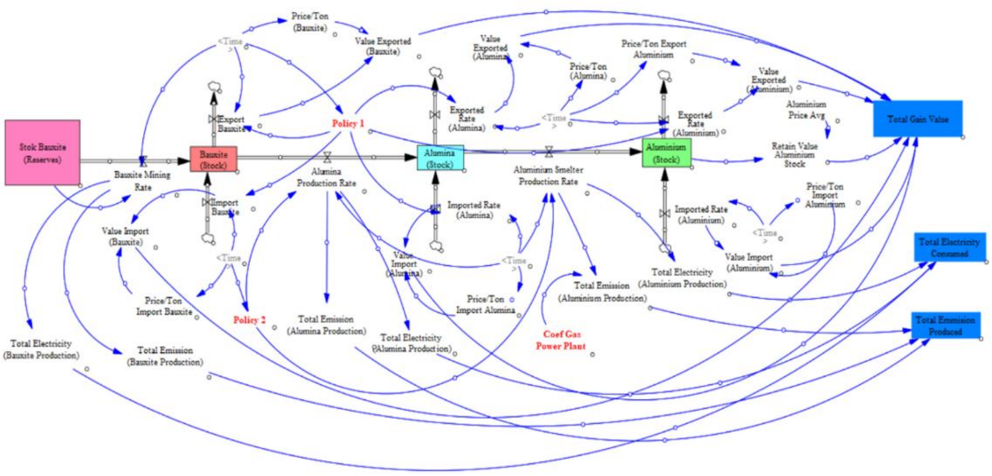


Figure 12. SFD Model-Scenario III

Results of Vensim Simulation Model Scenario III

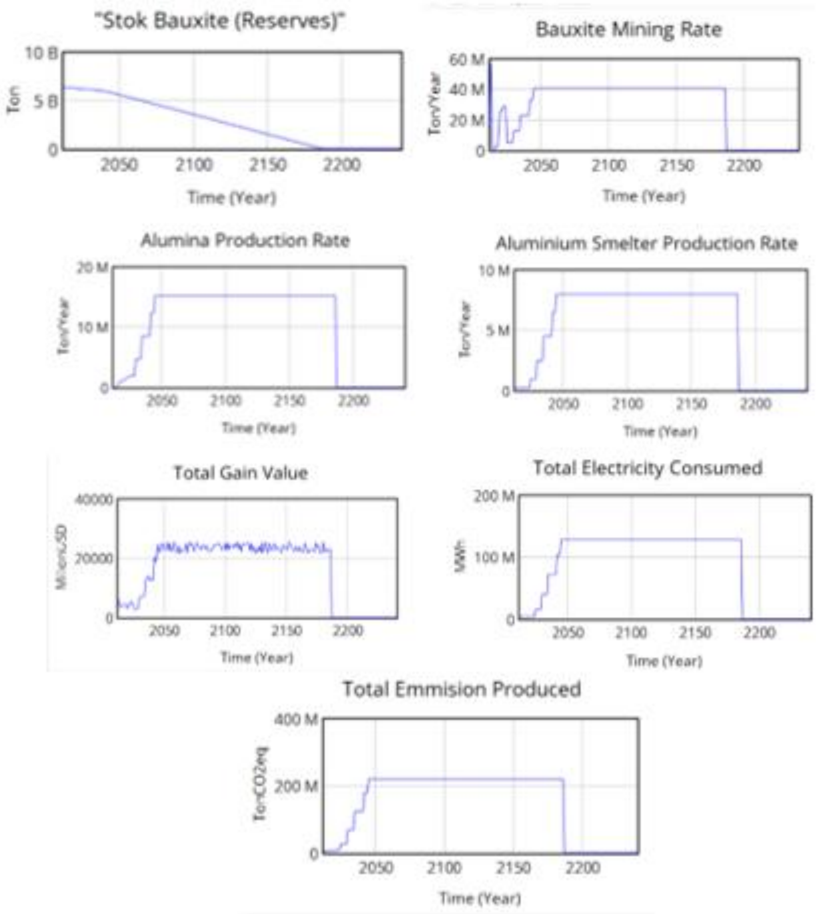


Figure 13. Results of Vensim Simulation Model Scenario III

Model Scenario IV

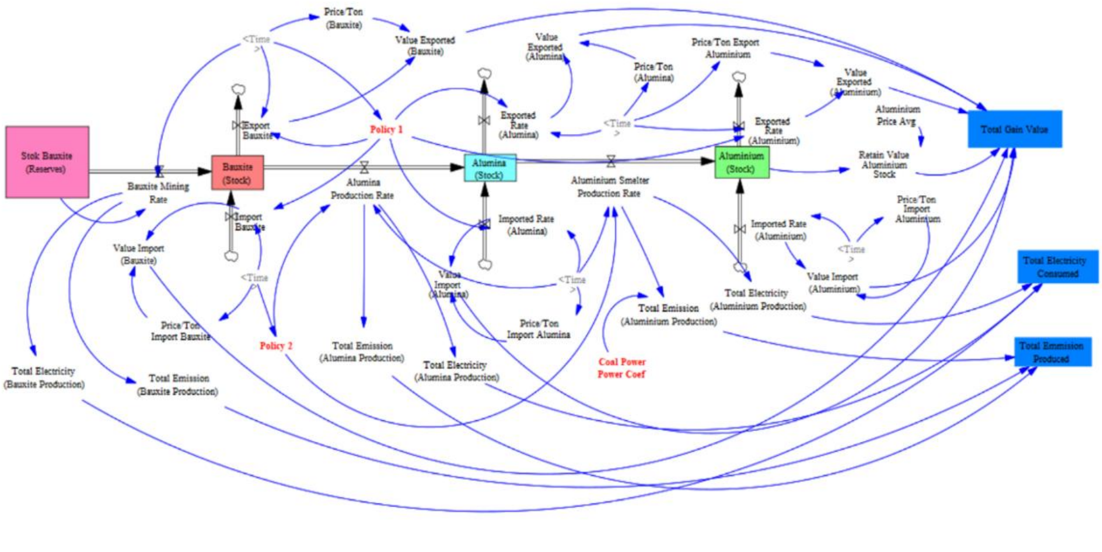


Figure 14. SFD Model-Scenario IV

Results of Vensim Simulation Model Scenario IV

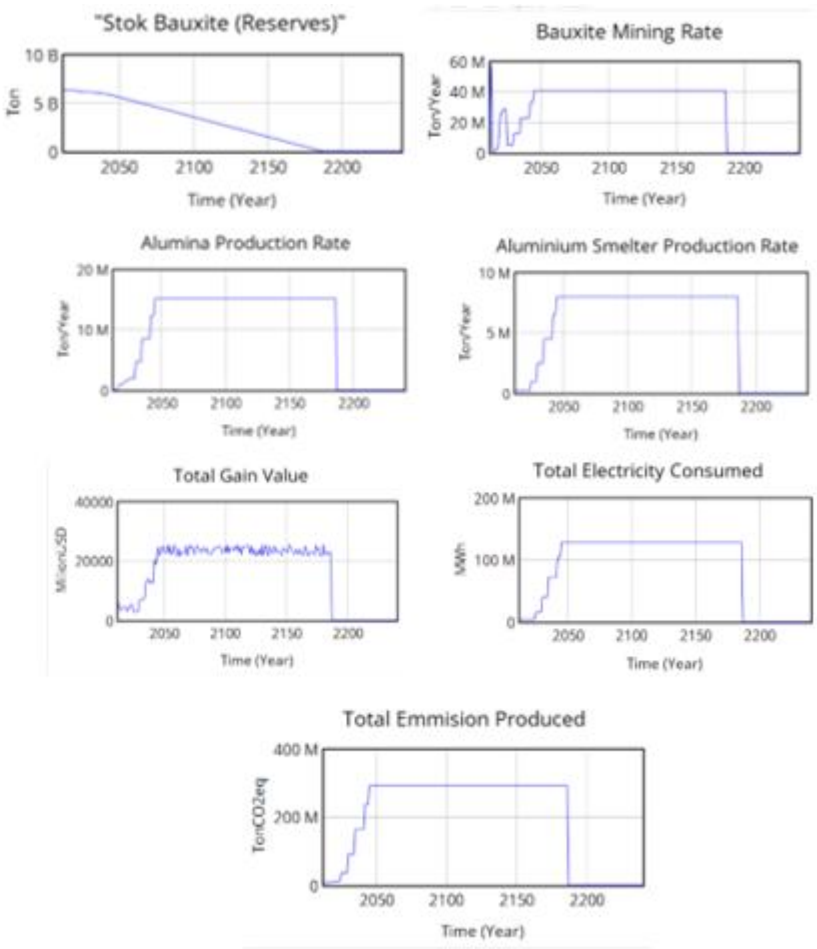


Figure 15. Results of Vensim Simulation Model Scenario IV

Comparison of Simulation Results for Various Scenarios

A detailed comparison between scenarios can be seen in the table.

Table 3. Comparison of simulation results for all scenarios in 2045

No Scenario	Year	Aluminum Production (Tons)	Total Added Value (Millions of USD)	Total Electricity (MWh)	Total CO2eq Emissions (Tons)
1	2025	264.5 thousand	5.691 *(92,6 T Rupiah)*	4,3 million	8,9 million
	2030				
	2035				
	2042				
	2045				
2	2025	1 million	3.100 *(50,4 T Rupiah)*	16 million	21,8 million
	2030	2,5 million	6.933 *(112,7 T Rupiah)*	40,2 million	54,6 million

	2035	4,5 million	12.852 *(209,1 T Rupiah)*	72,3 million	98,4 million
	2042	6,5 million	20.527 *(333,9 T Rupiah)*	104,5 million	142,1 million
	2045	8,0 million	24.936 *(405,7 T Rupiah)*	128,6 million	174,9 million
3	2025	1 million	3.100 *(50,4 T Rupiah)*	16 million	27,5 million
	2030	2,5 million	6.933 *(112,7 T Rupiah)*	40,2 million	68,9 million
	2035	4,5 million	12.852 *(209,1 T Rupiah)*	72,3 million	124 million
	2042	6,5 million	20.527 *(333,9 T Rupiah)*	104,5 million	179,1 million
	2045	8,0 million	24.936 *(405,7 T Rupiah)*	128,6 million	220,5 million
4	2025	1 million	3.100 *(50,4 T Rupiah)*	16 Juta	36,5 million
	2030	2,5 million	6.933 *(112,7 T Rupiah)*	40,2 million	91,4 million
	2035	4,5 million	12.852 *(209,1 T Rupiah)*	72,3 million	164,5 million
	2042	6,5 million	20.527 *(333,9 T Rupiah)*	104,5 million	237,6 million
	2045	8,0 million	24.936 *(405,7 T Rupiah)*	128,6 million	292,5 million

Based on Table 3, the simulation results show that the four scenarios have significant differences in aluminum production, added value, electricity consumption, and CO_2eq emissions until 2045. In scenario 1, aluminum production is relatively small (264.5 thousand tons) with added value of USD 5,691 million and emissions of 8.9 million tons of CO_2eq, reflecting limited industrial development. In contrast, scenarios 2 to 4 show rapid production growth, reaching 8 million tons in 2045 with added value of USD 24,936 million. However, this increase in production is accompanied by a surge in electricity consumption and emissions that differ in each scenario: scenario 2 produces the lowest emissions (174.9 million tons), while scenarios 3 and 4 show much higher emissions, 220.5 million tons and 292.5 million tons, respectively, in 2045.

Scenario Analysis

The next stage is the development and analysis of scenarios to explore various possible future policies and system changes. The scenario approach is used to understand the system's response to different interventions and identify the most effective and environmentally friendly strategies from the 4 vensim simulation scenarios.

Table 4. Vensim Simulation Scenarios

Scenario	Downstream Policy	Energy Sources
I	Business as Usual. Without intervention.	Hydroelectric Power Plant (Existing Condition)
II	Stop exports starting 2025 & increase domestic production (1, 2.5, 4.5,6.5, 8 million)	**Hydroelectric Power (Renewable Energy)**
III	Stop exports starting 2025 & increase domestic production (1, 2.5, 4.5,6.5, 8 million)	**PLTG (Natural Gas)**

IV	Stop exports starting 2025 & increase domestic production (1, 2.5, 4.5,6.5, 8 million) .	**Coal Power Plant**

In Scenario I, which represents the condition of business as usual without policy intervention, simulation results show that the availability of bauxite ore resources will experience a continuous decline and is projected to run out in 2237. This is due to the intensive bauxite exploitation pattern to meet export needs and alumina production simultaneously, without any restrictions on mining quotas, increasing the capacity of alumina refineries and aluminum smelters.

Meanwhile, in Scenario II, the simulation was made with policy interventions related to increasing aluminum production capacity gradually from 1,000 Kton to 8,000 Kton in 2045 with energy sources from hydroelectric power plants and the affirmation of export and import restrictions on the aluminum industry to be stopped starting in 2025. The use of electricity sources from hydroelectric power plants in this scenario is because aluminum smelters in Indonesia use this type of power plant, this hydroelectric power plant is a renewable energy that requires a fairly large investment value and needs to analyze more deeply the potential to be able to meet the electricity needs of this aluminum industry so that as an alternative in scenarios III and IV it is also necessary to consider how to utilize other power plants such as Gas Power Plants for energy transition and Coal Power Plants to utilize the large reserves of Indonesian Coal

The difference between scenario II, scenario III and scenario IV lies in the source of electrical energy used, which will also affect the amount of emission production in this industry. In scenario II, the energy source is from hydroelectric power plants, while in scenario III, the energy source is from gas-fired power plants and in scenario IV, the energy source is from coal-fired power plants.

Discussion

The declining bauxite reserves due to massive exploitation have not been fully offset by the increase in processing capacity into alumina and aluminum domestically. In addition, the national alumina and aluminum production capacity is still limited and not optimal, so that Indonesia still relies on exports of raw materials (bauxite) and imports of processed materials (alumina and aluminum) to meet the needs of the domestic industry.

This study was designed to develop a dynamic system model capable of simulating the long-term behavior of the Indonesian aluminum industry downstream system. This model is used to evaluate the impact of various policies and interventions through a scenario approach.

Table 5. Comparison of Improvement Scenarios for the 2045 Period

No	Scenario	Aluminum Production (KTons)	Total Gain Value (Million USD)	Total Electricity (GWh)	Total Emission (KTonCO2eq)
1	I	264,5	5.537 Equivalent to 90 Trillion	4.382	8.925
2	II	8.000	24.936 Equivalent to 405.7 Trillion	104.560	174.936
3	III	8.000	24.936 Equivalent to 405.7 Trillion	104.560	220.536
4	IV	8.000	24.936 Equivalent to 405.7 Trillion	104.560	292.536

Scenario I reflects the conditions if no significant policy intervention is carried out until 2045. In this situation, the utilization of bauxite reserves is still very limited, reflected in the still low aluminum that can be produced at only 264.5 Kton. The added value generated is only USD 5,537 million or equivalent to 90 trillion rupiah, reflecting the dominance of raw material exports with low added value. Electricity consumption is recorded at 4,383 GigaWattH, with total carbon emissions of 8,925 Kton CO_2eq.

Although the emission figures appear low, this is actually due to the low level of domestic industrial activity, not due to energy efficiency or sustainability. This scenario illustrates the structural weaknesses in the national industrial development strategy that still relies on exports of raw materials without further processing. As a result, the economic potential that could have been obtained from aluminum downstreaming is not utilized, and dependence on the global market remains high. This condition also creates long-term economic risks, especially if the global market imposes barriers to raw material exports or imposes carbon taxes on high-emission products. Thus, this scenario implicitly indicates the need for a transformation towards a more active approach in developing the domestic processing industry.

Scenario II represents downstream efforts through reducing raw material exports and increasing domestic aluminum production. The impact is very significant from an economic perspective, with the total profit value soaring to USD 24,936 million or equivalent to 405.7 trillion rupiah. With an increase in aluminum production in 2045 reaching 8,000 Kton, which reflects an increase in domestic aluminum production. Electricity consumption increases sharply to 104,560 GigaWattH, and carbon emissions soar to 174,936 Kton CO_2eq. Although this scenario has succeeded in increasing added value and strengthening the independence of the national industry, the environmental costs that must be borne are very large. Very high carbon emissions are a serious challenge, especially in the context of Indonesia's commitment to reducing emissions through the Paris Agreement and the Net Zero Emission target by 2060. This can also reduce the competitiveness of Indonesian aluminum products in the international market which is starting to demand environmentally friendly products [22]. In other words, although this scenario provides the best economic results, it poses a fairly high risk of environmental impact. Therefore, the downstream strategy must be balanced with clean energy policies and production efficiency so that environmental impacts can be reduced.

As an alternative to using electricity sources, Scenario III tries to combine industrial downstreaming with energy efficiency strategies through the use of natural gas, which is technically considered cleaner than coal. The total gain value and energy consumption remain the same as the second scenario, which is USD 24,936 million or equivalent to 405.7 trillion rupiah and 104,560 GigaWattH. However, the use of this transitional energy actually causes carbon emission production to soar higher to 220,536 Kton CO_2eq. This higher emission figure shows that although gas has a lower emission intensity per unit of energy than coal, its efficiency in the aluminum production process is not optimal [23]. In addition, there is a high probability of methane (CH_4) leakage in the gas production and distribution process, which has a much higher global warming potential (GWP) than CO_2. This scenario shows that energy savings do not necessarily result in emission reductions if they are not accompanied by changes to truly low-carbon energy sources. This is an important lesson that energy efficiency policy design must include a comprehensive analysis of fuel types, technologies, and energy distribution systems.

Another alternative scenario IV is the utilization of Indonesia's fairly high coal reserves with an efficient approach to electricity sources that still use coal fuel, but with cleaner technology or a system that can significantly reduce emissions. This scenario produces the highest total emissions in 2045 compared to the previous three scenarios, reaching 292,536 Kton CO_2eq. With an equivalent economic value (USD 24,936 million or equivalent to 405.7 trillion rupiah) and the same energy consumption, this scenario has the highest impact on the environment, but in terms of added value and electricity needs it remains the same compared to scenario II and scenario III. In this scenario, it is necessary to encourage the application of high-efficiency technologies such as ultra-supercritical boilers, carbon capture and storage (CCS) systems, or the use of coal with high calorific value that produces fewer emissions per unit of energy. This scenario is proof that the efficiency and utilization of coal as an energy source have not been able to create an optimal solution in the development of the aluminum industry.

The results of scenario II simulation show that optimizing the use of hydroelectric power plants in the development of the aluminum industry until 2045 is the most environmentally friendly scenario. However, the use of renewable energy is not yet fully optimized, so the use of natural gas as a transitional energy source is still needed to improve efficiency and control emissions from conventional energy sources. This approach enables the aluminum industry to reduce its carbon footprint compared to scenario IV, which is more dependent on fossil fuels, while still supporting the increase in domestic bauxite processing capacity and aluminum production.

A comparison with other industrial sectors, such as steel, provides additional perspective on emission reduction strategies. Research by Li et al. [23] shows that the use of green hydrogen as a substitute for natural gas in the steel industry can significantly reduce CO_2 emissions, although resource availability and investment costs remain challenges. In the aluminum sector, analysis shows a significant negative correlation between smelting energy intensity and primary aluminum production, where a 1-unit decrease in energy intensity correlates with an increase of approximately 10.76 units in production [24]. These findings underscore the importance of energy efficiency as a strategy for increasing production while reducing energy consumption. Overall, an integrated approach to energy efficiency and renewable energy utilization is key to the development of a sustainable aluminum industry, with positive impacts on productivity and the environment.

4. Conclusion

This study shows that dynamic system models can be used to quantitatively evaluate the impact of various scenarios for the development of Indonesia's aluminum industry. Scenario I shows that bauxite exploitation without proper management results in low added value and limited aluminum production capacity until 2045. Scenario II shows that increasing domestic production capacity can significantly increase economic value, but has an impact on increasing energy consumption and carbon emissions. Scenarios III and IV emphasize the importance of energy efficiency and fossil fuel management, with Scenario IV producing the highest CO_2 emissions. These findings confirm the need to implement a dynamic model-based monitoring and evaluation system in aluminum industry planning, so that decisions can be made based on data and considering the trade-offs between production, energy consumption, and emissions.

Declaration of AI and AI-assisted technologies in the writing process

The author confirms that no Artificial Intelligence (AI) tools were used in the development, writing, or preparation of this manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Arya J, Sigit A Wibisono, and dkk, “Neraca Sumber Daya dan Cadangan Batubara, Gambut, dan gas metana batubara,” in *Badan Pusat Sumber daya Mineral batubara dan panas bumi*, 2022.

[2] R. Aprillia, W. Mukhtar, S. Setiawati, G. C. Asbanu, and I. Munzir, “Genesis of Bauxite Ore in Toba Area Sanggau District, West Kalimantan Province,” *Jurnal Geocelebes*, pp. 26–36, 2024, doi: 10.20956/geocelebes.v8i1.26521.

[3] D. Brough and H. Jouhara, “The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery,” *International Journal of Thermofluids*, vol. 1, p. 100007, 2020, doi: 10.1016/j.ijft.2019.100007

[4] J. Dai, H. Liu, Y. Zhang, H. Shi, and P. Ling, "An Optimization Design of Energy Consumption for Aluminum Smelting Based on a Multi-Objective Artificial Vulture Algorithm," *Metals*, vol. 15, no. 2, p. 105, 2025, doi: 10.3390/met15020105.
[5] J. Safarov and R. Hasanov, "Green production management in the aluminum industry: A sustainable approach towards environmental performance," *Journal of Eastern European and Central Asian Research (JEECAR)*, vol. 11, no. 1, pp. 114–126, 2024, doi: 10.15549/jeecar.v11i1.1415.
[6] D. Ashkenazi, "How aluminum changed the world: A metallurgical revolution through technological and cultural perspectives," *Technol Forecast Soc Change*, vol. 143, pp. 101–113, 2019.
[7] E. Nordheim and G. Barrasso, "Sustainable development indicators of the European aluminium industry," *J Clean Prod*, vol. 15, no. 3, pp. 275–279, 2007.
[8] R. E. Sanders, "Technology innovation in aluminum products," *Jom*, vol. 53, pp. 21–25, 2001.
[9] S. Zhu, C. Gao, K. Song, M. Chen, F. Wu, and X. Li, "An assessment of environmental impacts and economic benefits of multiple aluminum production methods," *J Clean Prod*, vol. 370, p. 133523, 2022.
[10] A. Shen and J. Zhang, "Technologies for CO2 emission reduction and low-carbon development in primary aluminum industry in China: A review," *Renewable and Sustainable Energy Reviews*, vol. 189, p. 113965, 2024.
[11] A.-F. A. Rizzy *et al.*, "Impact of Aluminum Industry Development on Public Welfare and State Defense," *International Journal Of Humanities Education and Social Sciences*, vol. 3, no. 5, 2024.
[12] D. S. Oetomo, E. K. Dewi, and R. F. Ramdhani, "Analysis of the Development of Downstream Copper Industry in Indonesia to Obtain Maximum Added Value Using Dynamic Systems," *Journal of Information System, Technology and Engineering*, vol. 2, no. 3, pp. 287–296, 2024.
[13] M. Hanafi, "Designing nickel smelter industry investment competitiveness policy in Indonesia through system dynamics model," *Journal of Science and Technology Policy Management*, 2024, doi: 10.1108/JSTPM-01-2024-0016.
[14] L. Gozali, T. Y. M. Zagloel, T. M. Simatupang, W. Sutopo, A. Gunawan, Y. C. Liang, and Y. Suseno, "The important role of system dynamics investigation on business model, industry and performance management," *International Journal of Productivity and Performance Management*, vol. 73, no. 4, pp. 945–980, 2024, doi: 10.1108/IJPPM-07-2021-0399.
[15] S. I. Akbar and A. Nurpita, "PERFORMANCE ANALYSIS OF ALUMINUM INDUSTRY BASED ON PRODUCT LIFE CYCLE AND MARKET TRENDS," *Review of Management and Entrepreneurship*, vol. 3, no. 2, pp. 91–106, 2019.
[16] S. B. Abdinagoro and M. Hamsal, "Strategic Marketing Approach of Indonesia Aluminium Mineral Industry: Upstream and Downstream Analysis," *Journal The Winners*, vol. 23, no. 2, pp. 181–188, 2022, doi: 10.21512/tw.v23i2.9199.
[17] A. Muslih, P. Basoeki, and I. Iskandar, "300,000 TPY Aluminium Smelter Upgrading Project at PT. Indonesia Asahan Aluminium (Persero) in North Sumatera," *Saudi Journal of Engineering and Technology*, 2022.
[18] C. Boix-Fayos and J. De Vente, "Challenges and potential pathways towards sustainable agriculture within the European Green Deal," *Agricultural Systems*, vol. 207, p. 103634, 2023, doi: 10.1016/j.agsy.2023.103634.
[19] R. N. Ilham, K. A. Fachrudin, and A. S. Silalahi, "Positive Effect in Efficient Application of Corporate Social Responsibility in PT. Indonesia Asahan Aluminium as an Indicator Enhancement Efforts Public Welfare North Sumatra," in *2019 International Conference on Organizational Innovation (ICOI 2019)*, Atlantis Press, 2019, pp. 548–552.
[20] A. W. Wright, "The dynamic simulation and control of aluminium smelting cells," Doctoral dissertation, Newcastle University, 1993.

[21] A.-F. A. Rizzy *et al.*, "Impact of Aluminum Industry Development on Public Welfare and State Defense," *International Journal Of Humanities Education and Social Sciences*, vol. 3, no. 5, 2024.

[22] C. Zou, W. Gao, and F. Ai, "Strategic mineral policies for Indonesia: Enhancing global competitiveness, economic growth, and environmental sustainability through innovation and renewable energy," *Renewable Energy*, vol. 244, p. 122593, 2025, doi: 10.1016/j.renene.2025.122593

[23] J. Haraldsson and M. T. Johansson, "Effects on primary energy use, greenhouse gas emissions and related costs from improving energy end-use efficiency in the electrolysis in primary aluminium production," *Energy Efficiency*, vol. 13, no. 7, pp. 1299–1314, 2020.

[24] C. Li, L. Zhang, Q. Wang, and D. Zhou, "Towards low-carbon steel: System dynamics simulation of policies impact on green hydrogen steelmaking in China and the European Union," *Energy Policy*, vol. 188, p. 114073, 2024, doi: 10.1016/j.enpol.2024.114073

[25] J. I. Safarov, R. I. Hasanov, and A. Safarli, "Primary Aluminium Production and Energy Intensity: Long-Run Dynamics Explored through the ARDL Approach," *International Journal of Energy Economics and Policy*, vol. 15, no. 3, p. 17, 2025, doi: 10.32479/ijeep.18660.