Proposed scenario of low carbon development from waste sector in West Papua

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Abstract. The increasing of population and economic growth, urbanization, development progress and living standard has accelerated the rate and amount of waste generation. Waste is a serious problem of a worldwide concern because of its impact on environmental pollution, health and flood disasters in some drainages and rivers. Proper waste management is needed to reduce or prevent its negative impacts. For this reason, it is necessary to identify the types of waste and their potential to produce greenhouse gas emissions in order to obtain an accurate picture in an effort to formulate policies and strategies for reducing GHG emissions. The method used was thinking system and dynamic system by looking at the BAU scenario, 29%, 41% and 44% emission reduction. Based on the model of the dynamics system, a new scenario is needed through the intervention of waste processing by 3R at TPS and TPA, applying aerobic composting, methane capture and incineration.

1. Introduction

In line with the population growth, increasing income and living standards, urbanization and development will have an impact on increased waste production. An increase in various types of potential waste becomes a serious problem because the accumulation of waste can cause environmental damage and health problems. The trend of increasing global GHG emissions from solid waste management have been widely reported including [6,7]. To avoid or reduce the negative impact of waste, the management or proper handling is required according to the composition and characteristics of the wastes types.

There are four types of waste based on their shape or form, namely solid, liquid, gas and sound waste. Solid waste is the residue resulting from industrial activities or domestic activities in solid form and is known as waste. According to SNI 19-2452-2002, waste is solid scraps consisting of organic and inorganic materials which are considered useless and must be managed to the environment and safeguard development investment. Meanwhile, according to RI Law No. 18 2008, waste is the remains of human daily activities and/or natural processes in solid form. Examples of waste include paper, plastic, iron, wood, cloth, food waste and so on. Solid waste generally produces greenhouse gas emissions in the form of CH_4 and CO_2. The activity of burning waste produces CO_2, while open dumping in the landfill causes the accumulation of organic waste with anaerobic decomposition and produces CH_4 [4]. These gases are included in the greenhouse gases that contribute to global warming. To reduce greenhouse gas emissions, proper waste management is important.

West Papua Province with an area of 567 km^2, had a population of 765,258 people in 2010 but increased to 1,134,068 people in 2020 with a population growth rate of 2.65% and a gross regional domestic product of 5.2% per year [1, 5]. The increase in population and GRDP will have unavoidable consequences for an increased volume of solid waste, which can have serious impacts on the environment, social and economic. Therefore, solid waste management should be prioritized to reduce the impact of GG in the atmosphere.

Until 2021, West Papua province has a total of 8 FDA (final disposal area) with a total area of 49 ha and 475 TD (temporary disposal) units with a capacity of 475 m^3 spread across all districts. The average waste generation in West Papua Province is 0.518 kg/person/day or equivalent to 185.64 kg/person/year. However, the problem of waste in West Papua is that it has not been managed properly. TD in the form of garbage bins (containers) at various points of the area (TD transfer depot system) and the application of FDA systems of open dumping in each district show that waste management in West Papua has not been handled properly and mitigation efforts, especially for reducing carbon emissions. Waste management is aimed at reducing and dealing with waste generation by sorting and reducing and maximizing its utilization to provide positive value for the community and a positive contribution to low-carbon development. Until now, waste management at the TFD in West Papua is still carried out using an open dumping system. Open dumping is a waste management system in which waste material is left open and piled up in a final disposal location so that it can destroy the environmental and health conditions.

Another obstacle in building a waste management system in the province of West Papua is data collection. Data related to various waste variables is very minimal, this makes it quite difficult to calculate the contribution of GHG emissions from the waste sector and its management efforts to avoid environmental and social problems. The landfill extension program to accommodate solid waste can be executed, but without efforts to reduce waste sustainably through proper management or handling, GHG emissions massively increase. This study aims to build a dynamic system model for estimating waste generation and GG emissions, and to propose policies and strategies related to waste that can be managed with the right system to keep GG emissions at a minimum level following the capacity set in West Papua.

2. Methods

The data collected is in the form of the population and the amount of waste generated in West Papua, which are independent variables to obtain GG emissions waste. All data are formulated using a dynamic system model to simulate GG emissions and their interventions for mitigation actions. The system dynamics methodology includes two modeling steps: (1) Qualitative modeling known as a causal loop diagram (CLD) to show how different variables in an interrelated system, and (2) stock and flow diagram modeling (stock-flow diagram/SSWDS) to provide a better understanding of the system behavior by visualizing a well-off representation through simulation.

CLD is built based on these variables and relationships, and then the integrated CLD is converted into a stock-flow diagram (SSWDS), which describes the dynamic relationship between system quantities. The relationship between waste emission variables in this study was simulated using Powersim Studio 10 Professional.

The stock-flow diagram (SSWDS) is based on the principle of system dynamics which includes the state of level (accumulation or stock), flow/rate (input rate and output rate) and variables (Figure 1). System equations can be in the form of auxiliary, level, lookup, initial value, data and constants and are represented by symbols to be used in constructing the model structure and computer operations to perform simulations.

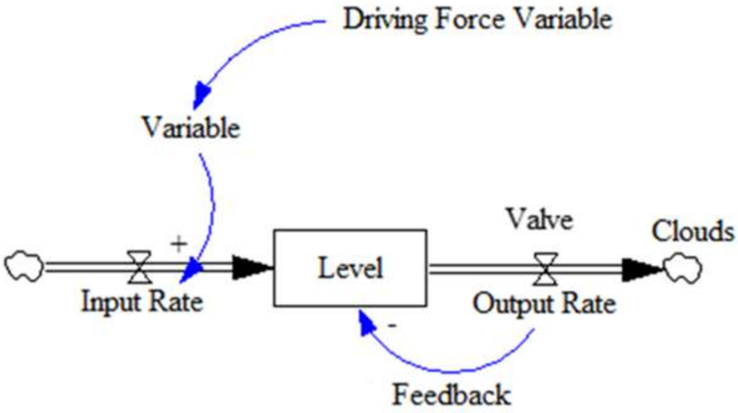

Figure 1. System Dynamics Model Structure

The structure notation of the system dynamics model with Powersim Studio 10 Professional software:
a. The stock or level is a fixed variable represented by a rectangular box;
b. Clouds represent sources or discharges that are outside the system or in the environment;
c. The incoming material flow (input rate) is represented as a pipe or arrow with a double line pointing to the stock. This flow will add material in stock;
d. The outflow of material (output rate) is represented as a pipe or arrow with a double line coming out of stock. This flow will reduce the material in stock;
e. Flow control expressed by a valve (valve);
f. Variables are expressed as variables and can be stated as constants or as driving variables (variables that affect the model but are not affected by the model;
g. The flow of information, represented by a single arrow, can be positive or negative;
h. Feedback indicates a causal relationship, where the arrowhead reveals the cause and effect.

Powersim helps to create stock and flow diagrams to represent larger system structures in detail with many interrelated workspaces and has a highly interactive user interface.

2.1 Model Validation

The statistical test was used to verify the model output with empirical data, namely by comparing the average value and calculating the error percentage of the average value. The average value (E_i) is calculated by the following formula [2]:

$$E_i = \frac{|\bar{S}-\bar{A}|}{\bar{A}} \tag{1}$$

with: $\bar{S} = \frac{1}{N}\sum_{i=1}^{N} S_i$, $\bar{A} = \frac{1}{N}\sum_{i=1}^{N} A_i$

Information : A = actual value, S = simulation value, N = Time

2.2 Variable determination and data collection

The main variables used in the system dynamics model are listed in Table 1. These variables include exogenous and endogenous variables. Exogenous variables are mostly leverage variables in the system dynamics model. When a small change is made in the variables, it will cause a large impact on the model.

Table 1. Variables for the simulation of the dynamic waste model

No	Name of the Variables	Unit	Source
1	Population	kg	BPS West Papua in 2011-2021, 2021 DLHP Waste Management Report.
2	Waste generation	kg	
3	Waste generation managed by the government (30%)	kg	
4.	Waste composition	%	
5.	Temporary Disposal (TD) Capacity	kg	
6.	Final Disposal/ Landfill Capacity	kg	
7.	Waste Bank	kg	
8.	Composting	kg	
9.	Processing 3R	kg	
10.	TD Capacity	kg	
11.	FD / Landfill capacity	kg	

2.3 BAU and Proposed Model

The BAU (Business as Usual) model provides an interlinked relationship between the total population and waste generation. These factors are vital to represent the growth rate of waste every year. This BAU model is the basis for designing the proposed scenario to achieve low carbon emissions from the waste sector. The proposed model includes several interventions as part of a scenario to reduce carbon emissions. The intervention is described as processing and processing waste at TDA and FDA to reduce the amount of waste and ultimately reduce GHG emissions.

3. Results and Discussion

3.1 Model Conceptualization

The generated waste in West Papua Province is equivalent to the population. The population of West Papua is determined by the birth rate and the imigration rate. While the population reduction is influenced by the death rate and outmigration rate. Population dynamics determine the changes in West Papua's waste generation. This waste generation will determine how much GHG emissions will be generated. This model also observes the amount of waste handled by the West Papua Provincial government and the amount of waste that is not handled. Therefore, in this model, a managed GHG emissions and abandoned waste was calculated. Waste management handled by the government will go through the stages of transporting waste to TDA and FDA. The amount of waste disposed in the landfill produce carbon emissions.Waste management at the TDA will be carried out by reducing waste, as a scenario for reduction policies (baseline, LCD-medium, LCD-High and LCD-Plus) in the form of changes in the level of 3R processing, composting and waste bank. Reduction of waste is also carried out at the household level, with a policy scenario of reducing waste generation per person per day.

3.2 Causal Loop Diagram

A causal loop diagram (CLD) visualizes how different variables in a system are related. CLD provides an overview of the SD model.

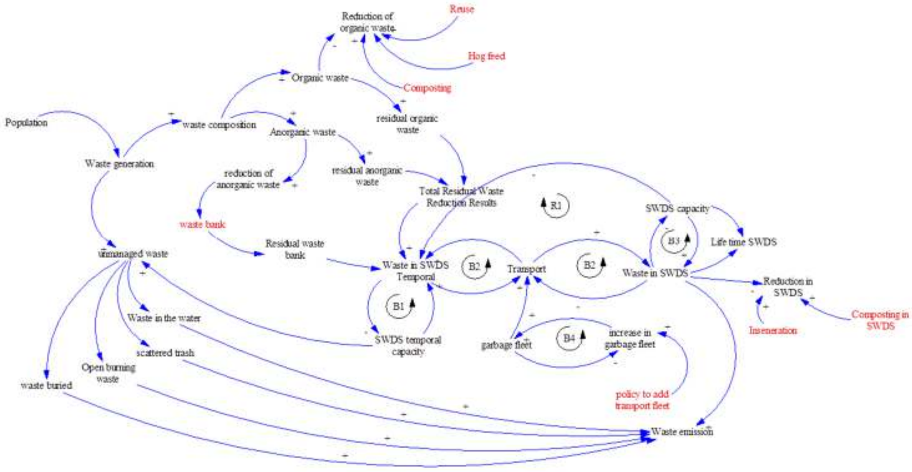

Figure 2. Causal Loop Diagram of Waste

In Figure 2, there is a causal relationship from one variable to another. Each arrow indicates the effect of one variable on the other because it has a positive (+) or negative (-) loop. Loop + shows that the relationship of the variable is directly proportional. If there is an increase in the value of the variable, it will cause an increase in the value of the variable it affects. On the other hand, a negative loop shows an inversely proportional relationship (not unidirectional) so that if there is an increase in the value of the variable, it will cause a decrease in the value of the variable it affects.

3.3 Stock-Flow Diagram

Stock and flow diagrams are the most common first steps in building a simulation model because they help determine the types of variables that are important in causing the behavior of the model. The stock-flow diagram of the pond sub-model is presented in Figure 3.

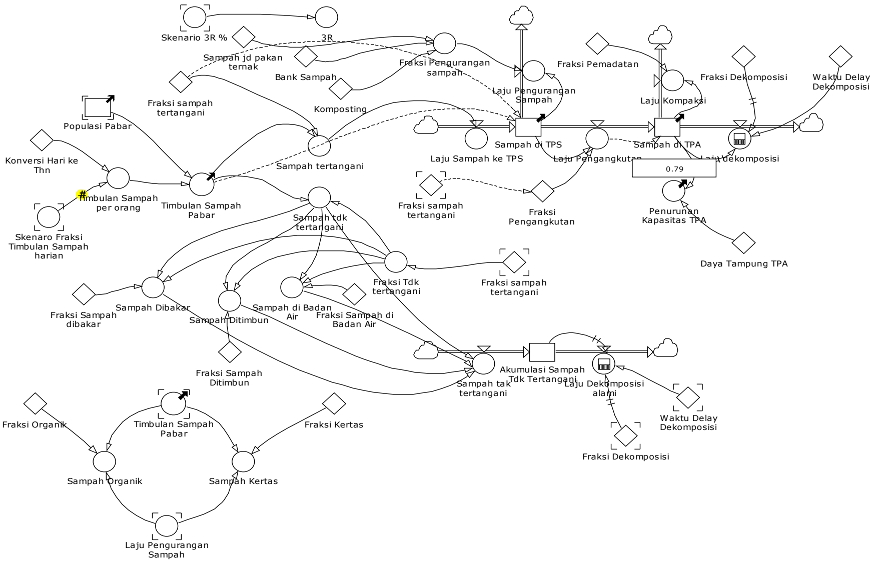

Figure 3. Stock-Flow Diagram (SFD) of Waste Sub-model of West Papua

3.4 Model Validation
The validation of the solid waste sub-model was carried out on the population and waste generation, by comparing the average value of historical data with simulations.

3.5 Population Sub Model Validation
The historical data on the population in 2010-2020 is used to validate the model (11 years). Validation was carried out for the population of West Papua in the population sub-model. The total population of West Papua varies each year and tends to increase from year to year (overtime). The average population growth rate is 3.08% with variations in the population growth rate between 2.46-3.94%. A very significant increase occurred in 2020, which is assumed to be influenced by the influx of residents from outside West Papua (immigration).

The result of calculating the error rate from the average value (Ei) obtained a validation value of 0.003 %. This means that the system dynamics model that is built can represent the actual condition of population growth over time because the percentage error value is <5% (Figure 4) [3]. stated that the deviation limit that is still acceptable is in the range of 5-10%.

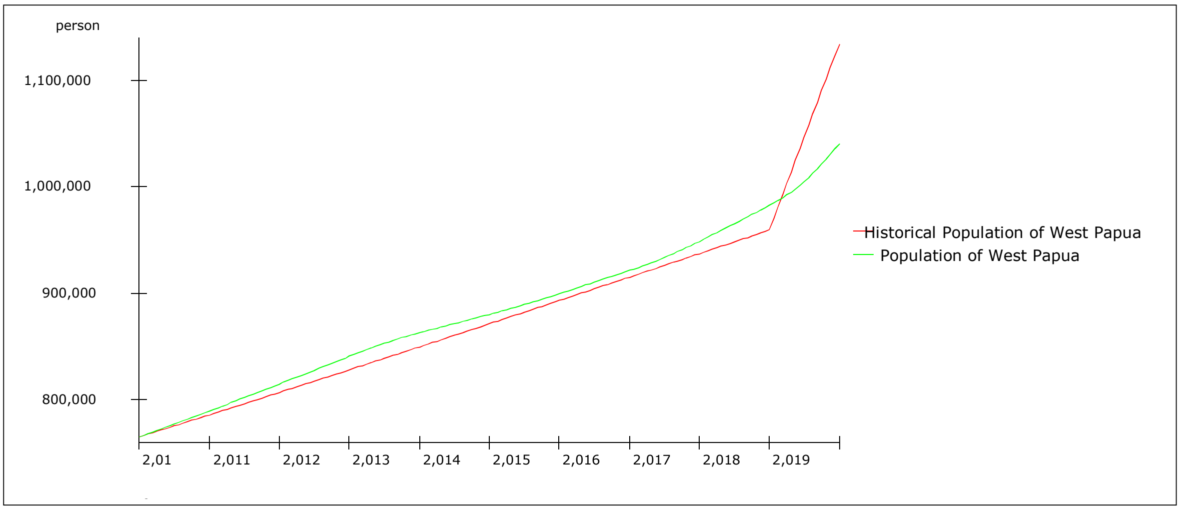

Figure 4. Comparison of Historical Population versus Simulation Data

3.6 Waste Generation Validation
The 2010-2020 historical waste generation data was used to validate the model (11 years). The value of waste generation varies every year and tends to increase from year to year, namely 133,234,195-178,567,625 kg/year (an average of 153,958.061 kg/day).

The result of calculating the error rate from the average value (Ei) obtained a validation value of 5.78%. This mean that the system dynamics model can represent the actual solid waste condition because the error percentage value is <10% (Figure 5) [3]. stated that the deviation limit that is still acceptable is in the range of 5-10%.

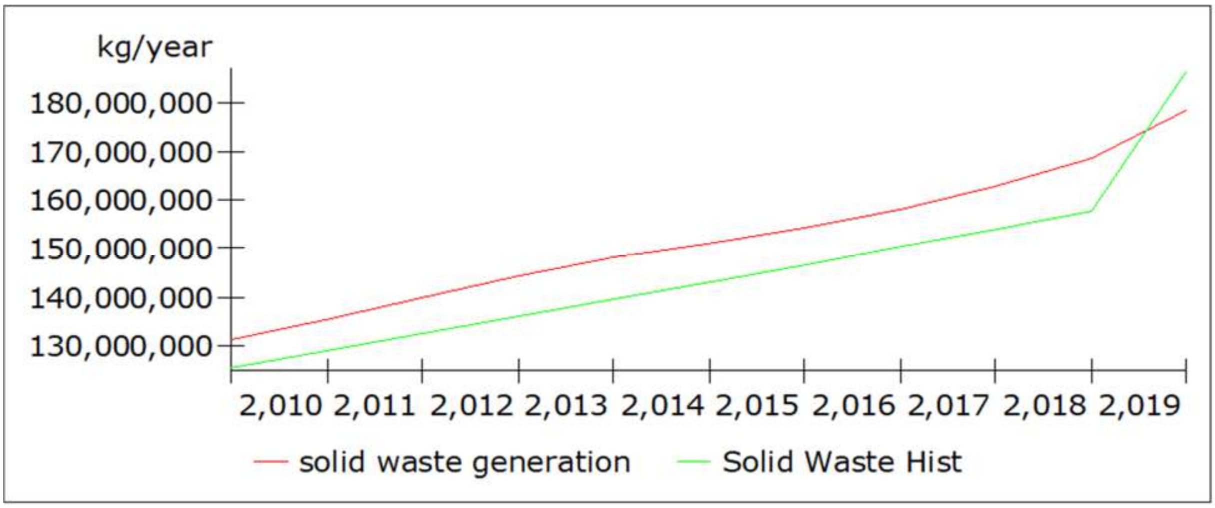

Figure 5. Data Comparison of Historical Waste Generation versus Simulation

3.7 Model Simulation

This model perform simulations using the four scenario approaches as follow:
1) Baseline: No new policy. However, it takes environmental degradation into account—This scenario reflects continuing historical trends. No new policies are introduced in this scenario.
2) Medium-LCD Scenario: Includes a new low carbon policy for 2020-2030; The scenario adopted is reduction at the source, namely reducing household waste generation from 0.51 kg/person/day to 0.4 kg/person/day, doing 3R processing by 5% and composting by 10%.
3) High-LCD Scenario: Covers more ambitious policies than the Medium LCD for 2020–2030; The scenario used is reduction at the source, namely reducing household waste generation from 0.51 kg/person/day to 0.4 kg/person/day, doing 3R processing by 15% and composting by 20%.
4) Plus-LCD Scenario: Includes HIGH LCD for 2020–30 and the implementation of additional, more ambitious policies thereafter. The scenario utilized is a reduction at the source, namely reducing household waste generation from 0.51 kg/person/day to 0.4 kg/person/day, doing 3R processing by 25% and composting by 30%.

3.8 Basic Assumption Scenario (Baseline)

The model simulation on the policy strategy with the baseline scenario has not provided new policies and still describes the continuation of historical behavior until the end of the simulation year.

Table 2. Waste generated at TDA, FDA, waste generation in West Papua, reduction in landfill capacity, total waste CO_2 emissions from 2010 - 2030.

Year	TDA Waste	FDA Waste	Waste Generation, West Papua	Decrease in FDA capacity (%)	Total CO_2 Emissions of Waste (kg*CO_2/year)
2010	42618748.54	12785624.56	142062495.12	98	105473543.94
2011	64089774.40	23921284.97	146649142.87	96	107389812.99
2012	79021117.09	37304945.52	151383875.70	94	109892204.42
2013	89800523.06	50749915.06	156178470.66	92	112620241.54
2014	97890098.34	63116729.26	160336824.60	90	114793788.32
2015	103997118.48	73859705.02	163535539.22	89	116807566.15
2016	108742810.97	82757672.94	167047146.24	87	119289380.29
2017	112744299.06	89850089.43	171058906.09	86	122092425.52
2018	116357375.72	95341331.36	175493692.58	85	125425198.34
2019	119895574.80	99503663.94	180670444.64	85	129904370.20
2020	123800652.61	102648997.93	192060983.22	84	141582409.90
2021	130427240.23	105371131.45	208922627.12	84	150316036.02
2022	137699587.63	108430547.06	216460677.36	83	155549349.12
2023	144310568.79	111715847.66	224270704.86	83	161039934.57
2024	150568813.34	115047366.21	232362522.70	82	166772436.89
2025	156674411.04	118355514.21	240746298.04	82	172739814.62
2026	162758070.84	121632239.78	249432564.90	81	178940448.44
2027	168906188.72	124901397.73	258432237.32	81	185376293.65
2028	175176896.04	128201053.16	267756623.18	80	192051701.58
2029	181610335.20	131573261.62	277417438.32	80	198972668.93
2030	188235240.33	135058484.80	287426821.30	79	203416055.35

Population growth has a positive correlation with the increase in waste generation. Part of this waste generation is not managed, and the composition of the waste generation consists of organic and inorganic waste. To reduce organic waste, three management strategies are needed, namely composting, for pig feed and 3R application, thus the generation of organic waste in the TDA (temporary disposal) can be reduced. In addition to reducing waste that lands in TDA, efforts to reduce waste at TDA are also useful to keep the capacity of waste at TDA from being exceeded. If the capacity of the waste in the TDA is exceeded, there will be scattered waste which will certainly increase GHG emissions. Furthermore, the remaining waste from the reduction will be transported to the FDA. Efforts to reduce both waste at the source and the TDA will also extend the service life of the FDA.

In its management, inorganic waste can be reduced by the availability of a waste bank, and this will minimized inorganic waste transported to TDA and FDA. So far, the handling of waste transportation from TDA to FDA is carried out by waste trucks. Waste transportation will run well if the number of transportation fleets is adequate, so the policy offered is to increase the number of waste transportations according to their capacity. To reduce the load on the capacity of waste in the FDA, it is necessary to handle waste through composting. Thus, waste reduction and management at TDA and FDA will reduce GHG emissions.

For unmanaged waste such as waste which enters water bodies, scattered on the ground surface. burned or enters the ground will have an impact on the increase of GHG emissions. It is hoped that with the addition of capacity and management at TD, unmanaged waste can be reduced.

The generation of waste at TDA is higher than FDA (Figure 6A), this is because several types of waste such as iron, aluminum that are disposed of at TDA are collected by waste collectors. 30% of waste is handled and the remaining 70% is unmanaged waste (Figure 6 B). Waste that is not handled is burned in the open by the community as much as 40%, 17.4% of waste is piled up by the community and 15% of waste is dumped in water bodies, while the rest is scattered waste.

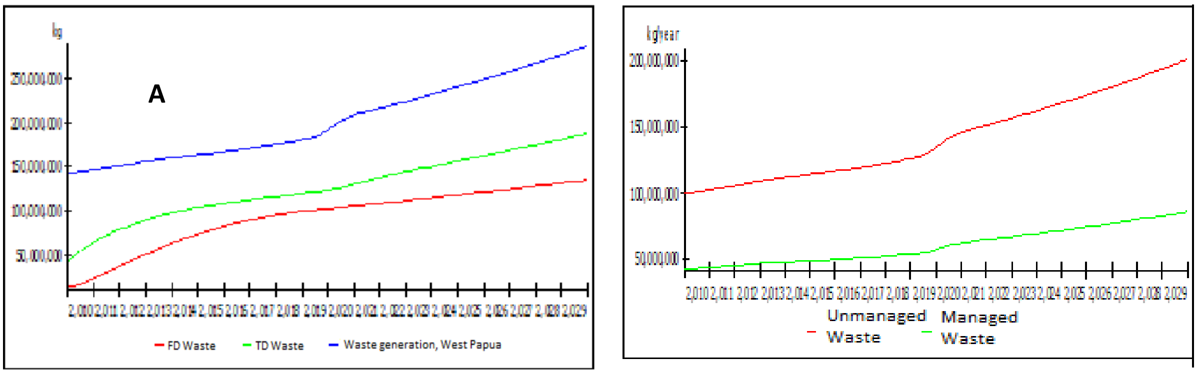

Figure 6. (A) The trend of increasing waste at TDA, FDA and West Papua waste generation in 2010-2030, (B) Amount of managed and unmanaged waste in 2010-2030.

In relation to the condition of the waste, the increase in waste generation causes a growth in CO_2 emissions from 105473543.94 tons CO2e in 2010 and will continue to increase until it reaches 203416055.35 tons CO2e in 2030 (Figure 7). The contribution of CO_2 emissions is dominated by FD which is managed by 78% open dumping, 3.4% waste burning activities, and 18.9% non-FD (scattered waste and marine litter).

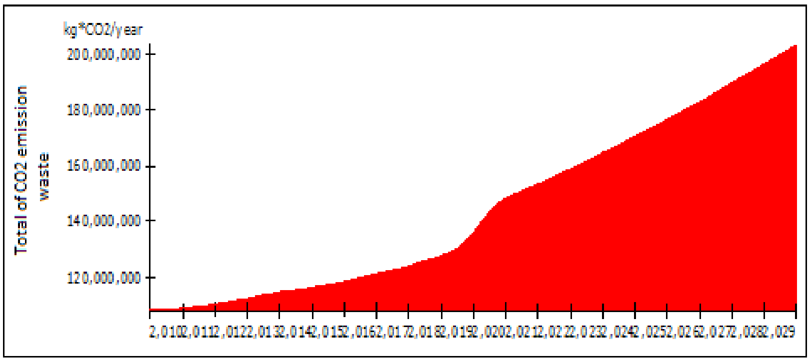

Figure 7. Trend of increasing CO_2 emissions of BAU waste from 2010-2030

3.9 LCD-Medium Scenario (Scenario 1)

This scenario is consistent with Indonesia's efforts to achieve the climate target desired by the West Papua provincial government, namely a 29% reduction in emissions by 2030 compared to the baseline. Scenarios is taken for new low carbon policies for 2020-2030; The scenario adapted is the reduction at the source, namely reducing household waste generation from 0.51 kg/person/day to 0.4 kg/person/day, 3R processing by 5% and composting by 10%.

This new LCD-Medium scenario is taken to intervene in the waste produced to align with the emission targets from the waste sector by proposing several policies in waste management as mentioned above.

Scenario 1, namely reducing household waste generation to 0.4 kg/person/day, 5% 3R processing and 10% composting can reduce waste generation by up to 22% compared to baseline. The level of waste generation reduction can be seen in Figure 8.

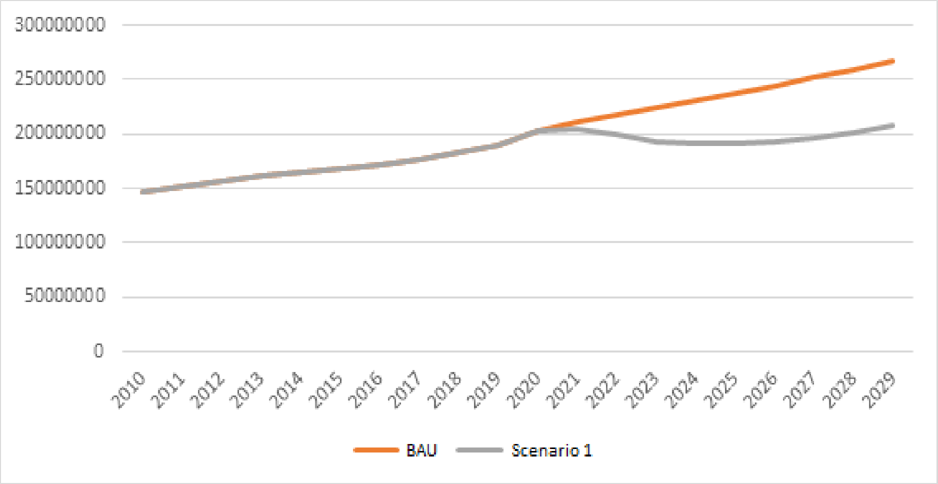

Figure 8. Reduction of Waste Generation in Scenario 1

The capacity of the landfill for waste collection efforts until 2030 in West Papua has not experienced any complications since the carrying capacity of the landfill has not been exceeded (Figure 9).

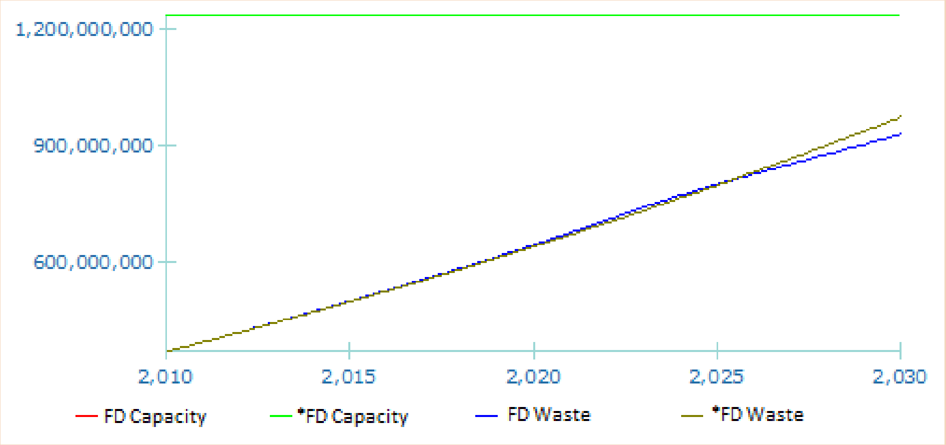

Figure 9. Capacity and Waste in TPA (kg) for Scenario 1

The level of reduction in waste emissions (tons of CO_2/year) in scenario 1 can reach an emission reduction of 18% (28647 tons of CO_2/year) (Figure 10).

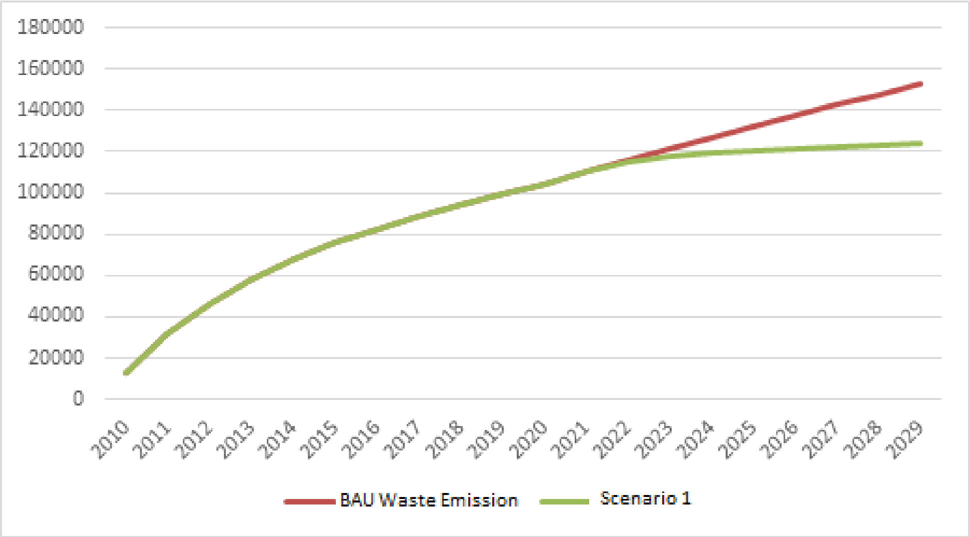

Figure 10. Waste emission reduction (ton CO2/year) for scenario 1

3.10 High LCD Scenario (Scenario 2)

These scenarios include policies that are more ambitious than the Medium LCD for 2020–2030. The scenario used is a decrease at the source, namely household waste generation reduction by 0.4 kg/person/day: 3R processing by 15% and composting by 20%. Reducing waste generation with policy intervention in scenario 2 can reduce waste generation by 22% or 60945183 kg (Figure 11).

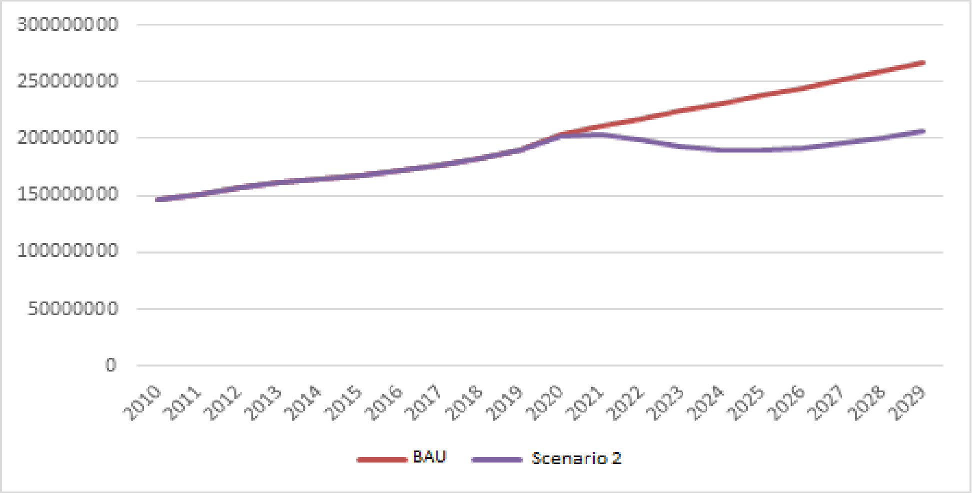

Figure 11. Reduction of Waste Generation in Scenario 2 (kg)

The capacity of the landfill against the efforts of waste collection until 2030 in West Papua has not experienced any difficulties because the carrying capacity of the landfill has not been exceeded (Figure 12).

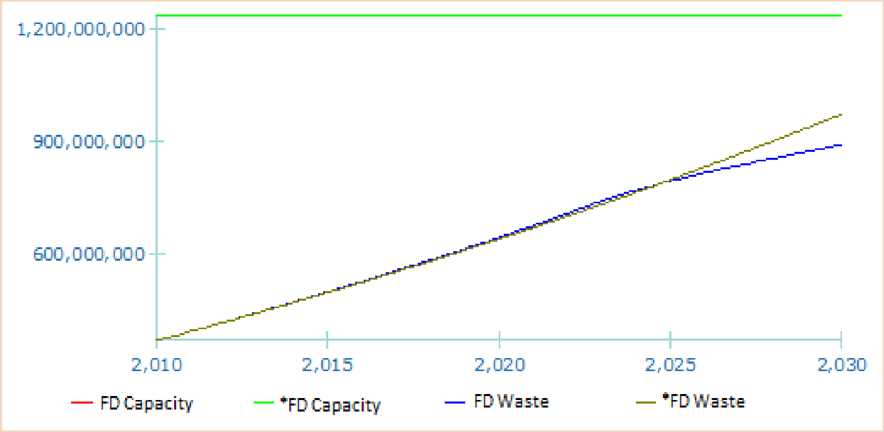

Figure 12. Capacity and Waste in TPA (kg) for Scenario 2

The composition of waste management is very dynamic, where the main composition is scattered waste, marine litter, burned and managed waste. The variation of managed and unmanaged waste is illustrated in Figure 13.

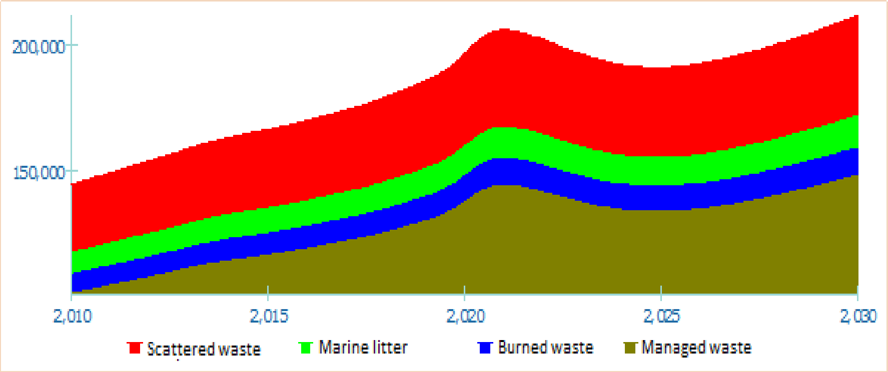

Figure 13. Composition of Waste Management Status (Scenario 2)

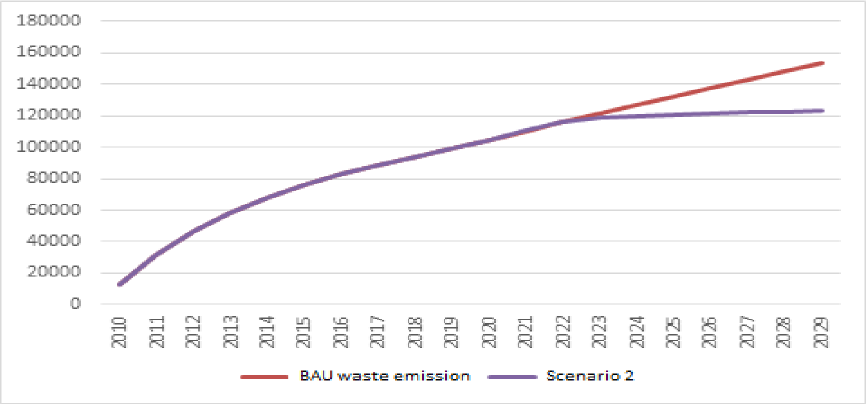

Figure 14. Waste Emission Reduction (tons CO_2/year) for Scenario 2

The level of reduction in waste emissions (tons CO_2/year) in scenario 2 achieves an emission reduction of 19% (29586 tons CO_2/year) (Figure 14).

3.11 Low Carbon Development (LCD)-Plus Scenario (Scenario 3)

Scenario 3 includes high LCD for 2020–2030 and subsequently, the implementation of additional and more ambitious policies. The scenario operated is a source reduction, namely a reduction in household waste generation by 0.4 kg/person/day, conducting the 3R processing by 25% and composting by 30%. Reducing waste generation with policy intervention in scenario 3 can reduce waste generation by 22% (Figure 15).

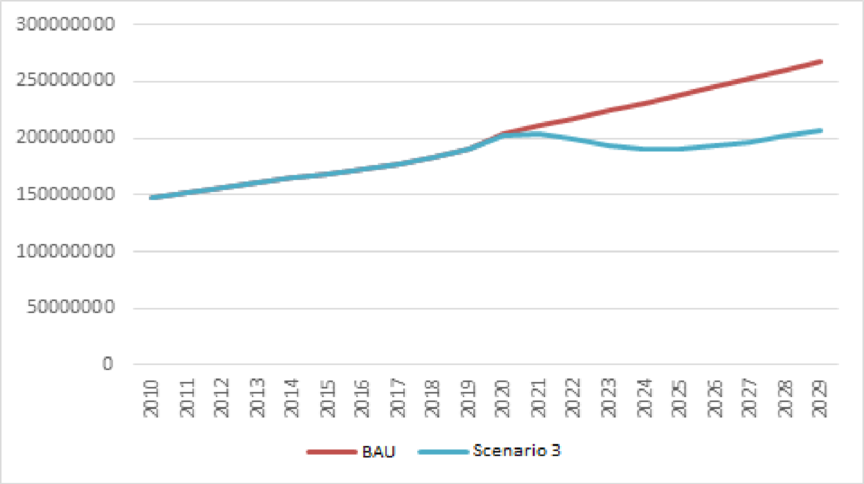

Figure 15. Waste Generation Reduction Scenario 3

The landfill capacity for waste collection efforts until 2030 in West Papua has not experienced problems because the carrying capacity of the landfill has not been exceeded (Figure 16).

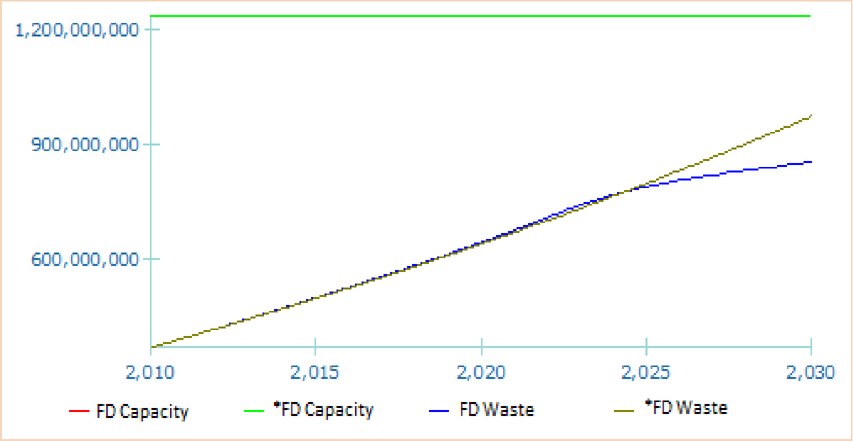

Figure 16. Capacity and Waste in FDA (kg) Scenario 3

The composition of waste management is very dynamic, where the main composition is scattered waste, marine litter, burned waste and managed waste. The variation of managed and unmanaged waste can be seen in Figure 17.

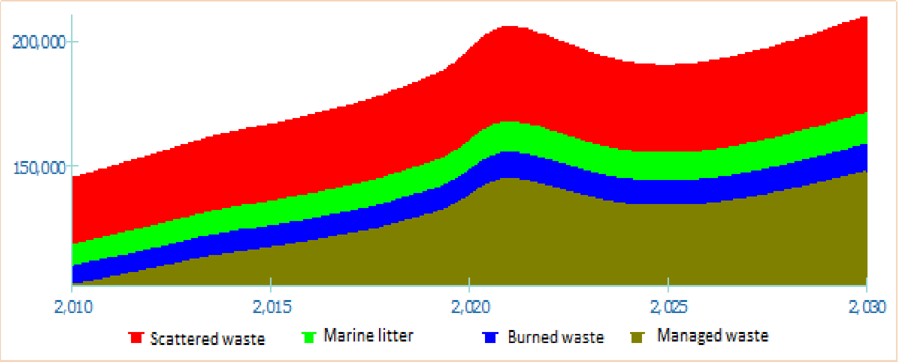

Figure 17. Composition of Waste Management Status Scenario 3

The level of waste emission reduction (tons CO_2/year) in scenario 2 can reach an emission reduction of 19% (29211 tons CO_2/year) (Figure 18).

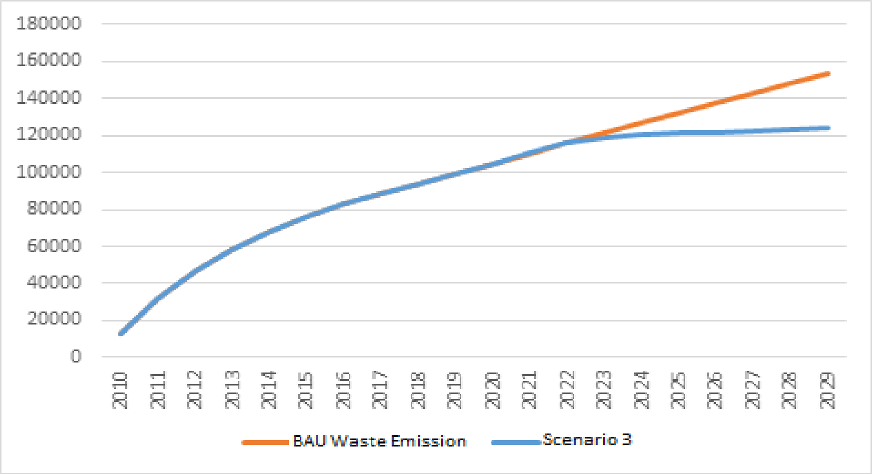

Figure 18. Waste Emission Reduction (tons CO_2/year) for Scenario 3

3.12 Proposed Scenario

Based on the simulation results using four policy interventions, GHG emissions were only reduced by 19%. Therefore, other policy interventions are still required. Other policies that can be adopted to reduce GG emissions are aerobic composting, applying methane capture, and incineration. Waste generation in West Papua is divided into manage and unmanaged waste. An increase in population will upsurge waste generation, thus it is necessary to increase the number of waste bins at TDA and the number of fleets to transport waste from TDA to FDA. To reduce the waste accumulation rate at TDA, waste must be managed through mitigation strategies to improve waste management and reduce GHG emissions. The 3R (Reduce, Reuse and Recycle) strategy and waste banks can be an option in managing managed waste at TDA. It is not only the capacity of the TDA that requires attentiveness in its management to reduce the fraction of waste transported to the FDA to control the concerns that arise on the issue of GHG emissions which continues to rise along with the rate of waste generation in the FDA. Therefore, it is necessary to intervene in waste management at the FDA by composting. The maximum composting technique must be applied to accelerate the decomposition rate; hence it can reduce GHG e missions. Compost (decomposed waste) will also have economic value as organic fertilizer. It will have a positive impact on the economic and social aspects.

For unmanaged waste due to burning, stockpiling and entering water bodies will decompose naturally. Nevertheless, the time depends on the type of waste and environmental conditions. For organic waste derives from the rest of living material, the rate of decomposition will be faster compared to other types of inorganic waste such as paper, plastic, cans and others.

4. Conclusion

GHG emissions produced by solid waste or waste in West Papua will continue to increase along with the increase in population and waste generation in both TDA and FDA. The system dynamics model shows that in 2030 waste generation in TDA and FDA will continue to rise along with the population growth so that waste generation in West Papua will increase its GG emissions by up to 123,832 tons of CO_2/year (scenario 3) or equivalent to a 19% reduction in GHG emissions. Therefore, a new scenario is proposed by implementing waste management interventions through 3R at TDA and FDA by aerobic composting, applying methane capture and incineration.

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