The Dynamics Model of the Waste Reduction to the Final Processing Site and Greenhouse Gas Emissions in Bogor City, Indonesia

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https://doi.org/10.5109/7326939

出版情報：Evergreen. 11 (4), pp.2983-2995, 2024-12. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan
バージョン：

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(Received January 27, 2024; Revised October 10, 2024; Accepted October 16, 2024).

Abstract: Increased waste generation is unavoidable, so an appropriate management system is needed. This research aims to predict the amount of waste reduction going into the Waste Final Processing Site (WFP), the reduction of greenhouse gas emissions, and electricity generated with the support of waste treatment technology using a combination of hydro-drive incinerators and Organic Rankine Cycle turbines. This research in Bogor City-Indonesia used a systems thinking approach with system dynamics methods that simulate various waste management scenarios until 2048. Simulation results show the projected life of the Galuga Bogor WFP only until 2028 because of overload capacity. One of the recommended management scenarios for waste management is the waste treatment scenario with the combination of these technologies (5-6 units), and composter, temporary shelter of 3R (Reduce, Recycle, Reuse), and waste bank grow 1% per year (scen-2c) where the projected waste that can be reduced is 7,734,757 tons, the electricity generated is 149,760,000 kWh, and the reduction of CO2e emissions is 6,574,544 tons.

Keywords: system dynamics; waste reduction; emission reduction; technology; waste to energy

1. Introduction

Solid waste generated worldwide annually is estimated to be no less than 2 billion tons of solid waste contributed by various anthropogenic activities. The increase in solid waste generation is due to urbanization, rapid economic growth, rising living standards, and changing lifestyles of urban residents[1]. The exponential increase in urban population has the potential to catalyze significant annual waste generation, which is projected to reach 3.88 billion by 2050, surpassing that of 2020[2]. The global economy largely operates on a linear, take-use-dispose model[3].

Socioeconomic changes such as population pressure, industrialization, migration, and urbanization have significantly increased municipal solid waste[4]. Improving the socioeconomic standards of the community affects the growth rate of waste generation[5]. Waste is a major urban problem because of its complex impacts, such as aesthetic, health, economic, and environmental losses that can lead to natural disasters and make the amount of GHG emissions from waste released into the atmosphere estimated to increase every year[6]. On the other hand, not all municipal waste management systems function properly, such as waste management facilities that are old or not managed according to standards, which causes air and water pollution, land degradation, harmful methane, leachate emissions, and climate change[7)]. Climate change is based on an increase in global GHG emissions[8)]. The trend of increasing consumption of various materials has also led to an increase in final waste production and the resulting environmental pollution, especially GHG emissions[9)]. Currently, dumping waste into landfills is the main way of waste disposal. With the increasing development of production, and demographic growth, the growth and accumulation of waste that causes environmental pollution has brought the daily living conditions of human beings into an unhealthy state and led to global climate change[10)]. Open landfills and landfills require large areas of land. Waste on open land creates a large amount of pollution and emits various toxic gases through decomposition, producing GHG emissions[11)]. WFP is commonly used for the final processing of solid waste worldwide[12)]. WFP have the potential to pollute by emitting large amounts of GHGs[12,13,14)]. GHG emissions from WFPs typically consist of 50-60% methane and 40-50% carbon dioxide, resulting from the biodegradation of organic matter disposed within the WFP[15)]. Most GHG emissions pollution from WFP waste occur during the first 16 years of WFP operation[12,16,17)]. Pollution from CH4 emissions alone can last for more than 100 years[12,17)]. In addition, there is a strong relationship between income and GHG (carbon dioxide) emissions, where countries with high per capita income will have a high carbon footprint[18)].

Urban waste management, including the development of waste management scenarios and optimization of waste management, is a key action aimed at reducing GHG emissions[19)] and making a positive contribution to low carbon development (LCD)[20)]. LCD supports the realization of a sustainable regional development program[21)].

Bogor City is part of Jabodetabek Megacity in Indonesia[22)] with a population of 1,114,018 people in 2022[23)]. The amount of municipal waste generated from Bogor City in 2022 was 271,727.6 tons and the waste transported to the Galuga WFP was around 195,787.1 tons[24)]. Not all waste in the Jabodetabek area is transported to the WFP, but some are dumped around the waste generator, burned, and dumped on vacant land or into rivers or waterways[25)]. Some are processed by waste banks, Temporary Shelter of 3R (Reduce, Recycle, Reuse) (TPS3R), Integrated Waste Management Site (TPST), and others. Bogor City's waste management still uses the collect, transport, and dispose method at the Galuga WFP. Only a portion is managed in waste banks, TPS3R, composting, and others to reduce the amount of waste sent to the Galuga WFP. The area of the Galuga WFP itself is limited to only about 38.7 hectares. In 2022, the waste sent to the Galuga WFP is around 195,787.1 tons/year, or 68% of the total waste[24)]. Municipal solid waste (MSW) without proper management can be a significant source of GHG emissions.

There were some technologies for solid waste treatment, especially on gas utilization which its produced. The technologies are flaring, Internal Combustion Engine (ICE), Gas Turbine, and Solid Oxide Fuel Cells (SOFC)[26)]. Except for flaring, these technologies can generate electricity. Solid waste incineration with power generation is recognized as a sustainable way to utilize waste[27)]. So to increase the reduction of waste sent to the Galuga WFP, waste management with Waste-to-Energy will be carried out, which is a process of generating energy in the form of electricity from waste. The quantity of urban waste will be more useful as a source of electrical energy than just being dumped in WFP. Initially, incinerators were only used to reduce the volume of waste produced in an area and to destroy hazardous substances that could cause disease. But now, waste incinerators are mostly combined with power generation[28)]. Renewable energy power generation is increasingly needed along with the development of several technologies from various resources, such as solar, biomass, geothermal, and marine power. One technology that also attracts research attention is the small-scale ORC for power generation that can be used in a region[29)]. The ORC can be used to generate electricity from low-temperature heat sources such as industrial waste heat, solar heat, geothermal heat, and others[30)]. Indonesia's National Research and Innovation Agency (BRIN) is developing a combination of hydrodrive incinerator with ORC turbine technology with a hydrodrive incinerator capacity of 2 tons of waste that can be processed per hour with an operational assumption of 15 hours/day (30 tons of waste per day) and an ORC turbine capacity to generate 100 Kw of electricity. This combination of technologies can be placed in a TPST that is close to the source of waste so that it can save waste transportation costs because the waste is destroyed directly near the source and has the advantage of being able to destroy waste by burning waste without using fossil fuels but using superheated steam generated by the furnace boiler in this system. ORC technology has a cycle that is almost the same as the technology in the Steam Rankine Cycle (SRC), which distinguishes only using organic liquids instead of water and works at heat source temperatures ranging from (40-250)^{o}C[31)]. ORC technology has proven to be a technology that can be used to convert this low to medium level heat source into useful power efficiently. Generating renewable energy and recovering waste heat is a potential solution that can effectively address energy source issues and severe environmental problems[32)]. Reducing the amount of waste that will be sent to WFP is the beginning of solving the waste problem because it can reduce adverse effects on the environment, while also reducing WFP land use[33)]. The reduced amount of waste sent to WFPs also reduces the amount of emissions that can cause GHG because many factors affect the amount of GHG emissions in waste disposal, such as the amount and composition of the waste, and how it is disposed of[33].

Ammonia (NH_3) emissions from solid waste significantly contribute to greenhouse gas emissions, especially during treatment processes like stripping and absorption[34]. The conversion of NH_3 to hydrogen (H_2) presents a significant opportunity to reduce GHG emissions, particularly in utilizing solid waste as a feedstock[35].

It is necessary to conduct research using a System Thinking approach with the system dynamics method to model the projected amount of waste reduction sent to WFP. This was some research on development system modeling in waste management. System dynamics-based simulation system integrated with Life Cycle Analysis was applied for plastics waste management[36]. Also, the system dynamic model was developed to reduce construction waste, particularly concrete waste, and strategic investments in training and policy[37]. This model was built to predict the development of the waste reduction capability of the Bogor City waste treatment system. So that it can predict the amount of waste reduction sent to the Galuga WFP and the reduction of GHG emissions and anticipate if problems arise such as a full WFP. The policies can be taken to prevent a waste emergency that will occur in the next few years due to a full WFP. The model built is expected to describe the relationship between components, feedback, optimization, and its impact; so that it becomes more effective, optimal, and sustainable from Galuga WFP based on simulations and scenarios. System dynamics represents one of the complex system modeling methods that improve understanding of dynamic complexity and sources of policy resistance, in addition to designing more effective policies[38,39]. System Dynamics is a method for explaining systems using qualitative and quantitative models and using feedback types of information that shape behavior, feedback structures, and control policies[40]. In addition, System Dynamics is a method to improve learning in complex systems[39]. The scenarios in waste management in Bogor City from 2018 to 2048 were simulated. Scenarios with the addition of Hydrodrive incinerators and ORC turbines every five years and other scenarios and also the addition of capacity from existing processing such as TPS3R, composting, and waste banks. The scenarios carried out are expected to fulfill the capacity to reduce the waste generated by the growing population in Bogor City. This reduction in the amount of waste sent to WFP is expected to extend the life of the Galuga WFP. Even gradually until almost no waste is sent to Galuga WFP by 2050, as the Bogor City Government expects. In addition to reducing the amount of waste sent to Galuga WFP and GHG emissions. Also, electricity will generated that can be used by the surrounding community, and there will be no need to expand the WFP. These efforts will significantly support low-carbon development in Indonesia.

2. Materials and methods

The system dynamics model was built to project the annual reduction of the amount of waste sent to the Galuga WFP from the waste management system in Bogor City. Also, reduction policy scenarios can be carried out. This model was built based on the phenomena and behavior of factors in the waste management system in Bogor City. A dynamics model design uses Powersim software.

The data collected are primary and secondary. Phenomena and behavior were obtained by direct observation in the field, in-depth interviews, and Focus Group Discussions with several key actors related to municipal waste management in Bogor, i.e., the government, NGOs, experts, and waste managers.

Secondary data collected include the population, the amount of waste generated, the capacity of TPS3R, composting, waste banks, and others, the land area of the Galuga WFP, and also data on the percentage of waste that has been reduced.

System dynamics is unique in its ability to represent the real world and can accept the complexity, nonlinearity, and feedback loop structure inherent in social and physical systems[41]. Complex dynamic relationships between factors and policy linkages can be investigated by system dynamics models[40]. Understanding the structure and behavior of a system with non-linear relationships and feedback can also be assisted by system dynamics models[42,43]. Based on the phenomena that occur in the waste management system in Bogor City, a CLD is created, where CLD is a causal diagram that helps in visualizing how various variables in a system are causally interrelated. The next stage of CLD is developed in software into a Stock-Flow Diagram (SFD). SFD is depicted in a diagram consisting of 2 types of variables namely stock (level) and flow (rate), where stock (or level) consists of accumulation in the system, while flow (or rate) is the transportation of some content from one level to another[44].

In the SFD that has been built, verification and validation tests of the model are carried out. Verification is carried out to ensure that the computer program and conceptual implementation representing the actual model do not introduce errors after inputting the model formulation to the variables in the stock flow diagram. After verification, model validation is carried out. Model validation aims to ensure that the behavior of the simulated model matches the observed behavior, or the actual behavior of the system it represents[45].

Verification will be carried out on the formulation (equation) and units of model variables. Verification using Powersim software on unit and equation testing because this software can only run models with unit consistency and equation formulation.

Model validation uses a quantitative validation approach with a statistical measure, namely Mean Absolute Percentage Error (MAPE). MAPE measures the accuracy of a forecasting method by calculating the average absolute percentage error between the predicted value of the model and the actual observed value[38,42] with formula (1).

$$MAPE = 1/n.\sum(abs(X_m - X_d))/X_d \times 100\ \% \quad (1)$$

X_m = Simulation Results, and X_d = Data
The criteria are:

- MAPE < 5 % : very appropriate
- 5 < MAPE < 10 % : appropriate
- MAPE > 10 % : inappropriate

A model is a simplified form of the actual event, limited by the aspects that are the focus and emphasized in the analysis. The model limitation only includes variables related to the flow of material (waste) from generation in the community to the WFP. The Bogor City waste processing facilities included in this model are TPS3R, Waste Bank, Composting, and TPST, then the residue is disposed of at WFP. TPST is a waste processing facility with a large capacity, whereas, in this model, it uses a hydro drive incinerator waste processing system with an ORC turbine that can generate electricity from the heat generated. This is because the current waste management system in Bogor City is unable to cope with the amount of waste generated each year.

Apart from the material flow (waste), the model also discusses the amount of CO_2e emissions that can be reduced using various scenarios by increasing the waste treatment capacity and how much economic benefit can be obtained from each type of waste management.

In the built model, several simulations of various alternative scenarios were carried out to achieve the goal of reducing the amount of waste sent to the Galuga WFP and reducing GHG gas emissions from reducing the amount of waste sent to the Galuga WFP as well as EBT results in the form of electricity generated with the desired ORC turbine Hydrodrive incinerator usage policy. The projection period is 30 years (2018 to 2048). The results of this modeling also anticipate the emergence of problems in the next few years such as full WFPs. In the best scenario, it is expected to gradually reduce the amount of waste until almost no more waste is sent to WFP in 2050 as per the policy of the Bogor City Government. For modeling work steps see Fig. 1.

3. Results and discussion

3.1 Description of Bogor City

Bogor City with an area of 11,850 ha has a population of 1,114,018 people (December 2022), with an average population growth of 2.0% during 2018-2022. Population data for Bogor City from 2018-2022, waste, and waste sent to the Galuga WFP can be seen in Table 1.

The amount of waste generated by the population of Bogor City in 2022 reached around 271,727.6 tons/year with details of 40% food waste, 20% paperboard; 15% plastic; 14% wood/framing; 1% metal; 2.5% fabric; 0.5% rubber/leather; 1% glass; 6% other (SIPSN). The data - data on the amount of waste reduction, the amount of waste managed, and the achievement of waste management in Bogor City in 2022 as shown in Table 2.

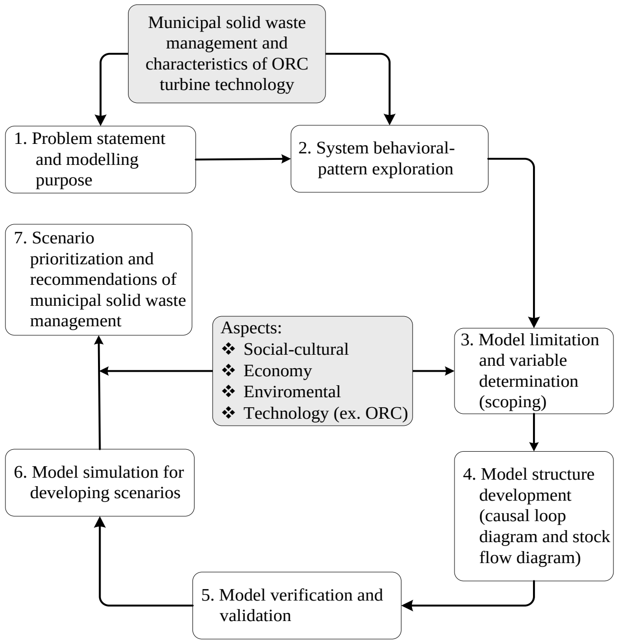

Fig. 1: Municipal solid waste management modeling stages.

Table 1. Amount of population[23),]waste, and waste sent to Galuga WFP[24].

Years	Amount of population (people)	Amount of waste (ton)	Amount of waste sent to Galuga WFP (tons)
2018	1,096,828	226,581	182,850
2019	1,048,610	240,205	185,064
2020	1,043,070	245,922	185,465
2021	1,052,359	245,922	186,844
2022	1,114,018	271,728	195,787

Table 2. Bogor City waste management achievement in 2022[24]

Waste Management	Ton/Year	%
Waste Generation	271,727.6	-
Waste reduced	63,382.6	23.3
Waste sent to WFP	195,787.1	72.1
Unmanaged waste	12,557.9	4.6

The dynamic system model from the data obtained is made to predict the amount that can be reduced from the waste sent to the WFP. To increase the amount of waste that can be reduced, a processing process will be added using a hydro-drive incinerator combined with ORC turbine technology, and increase the capacity of existing processing systems such as TPS3R, composting, and waste banks.

3.2 Causal loop diagrams (CLD)

CLD are a basis to represent the feedback structure of complex systems. CLD uses problem-solving by looking at the system complexity depicted by a diagram of a curved line tipped with arrows connecting one factor to another. Each arrow in the CLD has a "+" sign and a "-" sign. These "+" and "-" signs indicate the relationship between one factor and another. The "+" sign indicates a mutually reinforcing relationship, namely that if the causal factor or influencing factor increases, the effect factor or influenced factor will also increase which changes dynamically in line with the development of time while the "-" sign is a mutually weakening relationship, namely that if the causal factor or influencing factor increases, the effect factor or influenced factor will decrease. In a CLD, if the impact leads to a certain equilibrium, the loop is marked with "B". If the causal loop results in exponential impact or degradation, it is denoted by the letter "R"[39]. The CLD of the waste management model can be seen in Fig. 2.

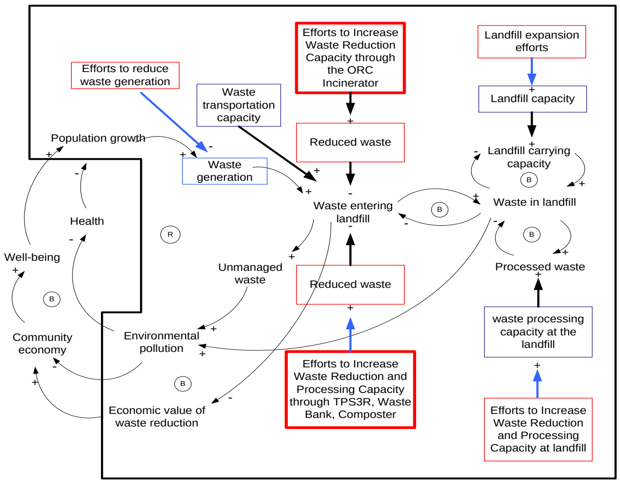

Fig. 2: Causal loop diagram of waste management model.

In the case of the waste model above, it can be seen that the waste generation that causes pollution is exponential or continues to increase (marked with "R"). In contrast, the ability of WFP or landfill to accommodate waste has limitations (marked with "B"). Efforts to balance waste generation growth can be made at the WFP or reduce waste before entering the WFP. Due to limited land, the effort to reduce waste before entering WFP is highly considered, especially since it can generate economic value, even though the value is towards a certain equilibrium.

Bogor City's waste generation is determined by the population growth and waste production per resident per day. This waste generation affects the amount of waste sent to the WFP. If all waste generation can be handled and managed, there will be no remaining waste, so this depends on the fraction of managed waste. Unmanaged waste will cause effects on the environment such as beauty, cleanliness, and public health. The capacity or capacity of TPS3R, composter processing, waste banks, and other processing systems is influenced by the ability factors to absorb waste from the waste processing in Bogor City. The greater the capacity and capacity of the processing system will affect the waste generation factor sent to the WFP. The waste that enters the WFP is influenced by the large fraction of unmanaged waste generation and is also influenced by the remaining waste from processing in TPS3R and other processing. Due to the limited capacity of temporary WFPs, waste must be immediately transported and sent to WFP because otherwise, it will harm the surrounding environment which is usually close to residential areas. To reduce the amount of waste sent to the WFP, waste processing will be applied by using a Hydrodrive incinerator combined with ORC turbine technology around temporary WFP that can reduce waste by processing waste without having to be sorted first, where the Hydrodrive incinerator with a combination of ORC turbine technology in addition to reducing the amount of waste also produces electricity that can be used for the surrounding area. Reducing the amount of waste sent to the WFP can extend the WFP's lifespan and reduce CO_2e emissions.

3.3 Stock-flow diagram (SFD)

SFD for the Bogor waste management model is based on the explanation in the CLD. SFD can be seen in Fig. 3. The basic principles of this modeling are as follows:

- The model is simulated for 30 years from 2018-2048. The data used for modeling is data from 2018 - 2022.
- Waste generation is based on population, so the annual increase follows the population growth. Population growth follows the average population growth from 2018 to 2022 of 2%.
- Waste generation per person per day is calculated based on an Indonesian National Standard SNI 3242-2008 for large cities:
  - waste generation per person is 3 liters/person/day,
  - assumed specific gravity of waste is 0.2-0.3 kg per liter,
  - if a specific gravity of 0.25 kg per liter is taken,
  - waste generation is 3 x 0.25 kg/person/day = 0.75 kg/person/day,
  - in 1 year is 0.75 x 365 days = 273.75 kg/person/year = 0.27375 tons/person/year.
- From the waste generated, under current conditions based on existing 2022 data, waste is reduced by:
  - waste bank's ability to reduce 1,188 tons per year from 1,217 tons of incoming waste (97.62%). Products produced of recycled raw materials amounted to 787 tons per year (66.22% of the weight of managed waste). The number is 137 Bank Sampah Unit (BSU) and 1 Bank Sampah Induk (BSI).
  - composting activities are carried out by 68 small-scale composting units and 1 compost house unit with a waste processing capacity of 57,568 tons from 57,571 tons of incoming waste (99.99%). Products produced in the form of compost raw materials amounted to 57.568 tons (100% of the waste processed weight).

- TPS3R are 28 units with a processing capacity of 4,626.62 tons out of 7,762.88 tons of incoming waste (59.68%). The products produced of animal feed raw materials, recycled raw materials, and compost raw materials amounted to 4,626.62 tons (100% of managed waste).

- Galuga WFP has a area of 38.7 ha. If the waste is piled up to 20 meters, the capacity is 7,740,000 m^3 or 1,935,000 tons. Waste entering the WFP from 2022 data is 195,787.1 tons and entering the WFP is 185,399.2 tons (94.68%). With a capacity of 1,935,000 tons of WFP, if the reduction capacity is not increased before the waste enters the WFP, the WFP will only be closed until 2028.
- The capacity of the hydro-drive incinerator is 30 tons/day and the capacity of the ORC turbine generator is 100 kW.

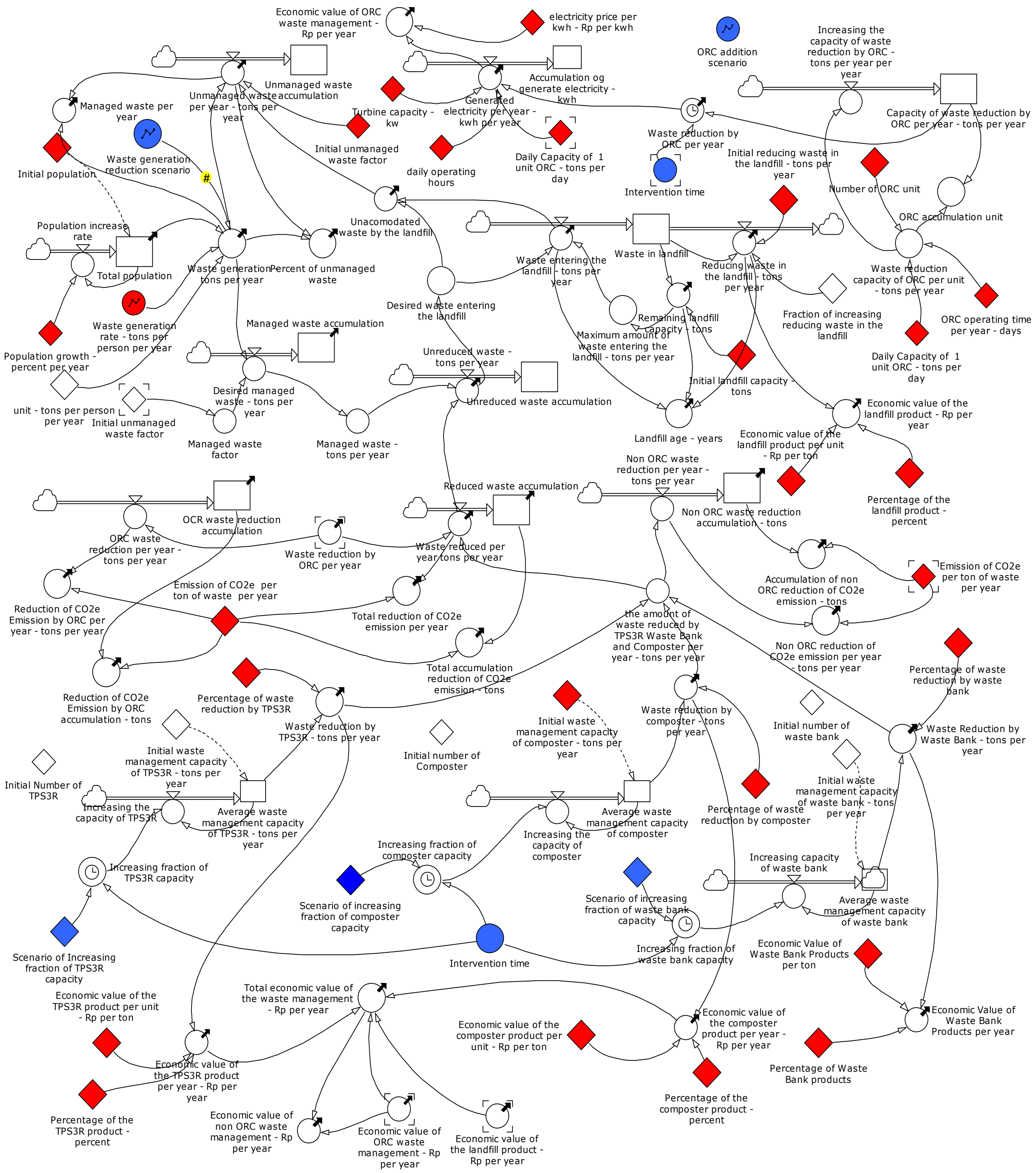

Fig. 3: Stock flow diagram of waste management model in Bogor City.

- The reduction amount prediction of CO_2e emissions can be calculated from the waste reduced amount sent to the Galuga WFP. The composition of waste is not uniform in each WFP, specific gas production and gas composition from one WFP can be different from other WFPs[25)]. It also depends on the type of WFP. CO_2e emission factors for open dumping WFPs are around 688-963 kg CO_2e/ton of waste, conventional WFPs with mixed waste (50% organic, 50% inert waste) 58-327 kg CO_2e/ton of waste, engineered WFPs with gas utilization 58-327 kg CO_2e/ton of waste, and low organic waste WFPs 19-74 kg CO_2e/ton of waste[46)]. In this research, to calculate the prediction of CO_2e emissions, a CO_2e emission factor value of 850 kg CO_2e/ton of waste will be taken because the Galuga WFP used an open-dumping WFP type. This emission factor is multiplied by the weight of the reduced waste to obtain the emissions from the reduced waste.

3.4 Increasing waste reduction capacity

To reduce waste entering the WFP, where this is done to extend the life of the WFP or to carry out sustainable WFP management, efforts are made to reduce waste before entering the WFP such as:

- reducing waste generation rate.
- increase the processing capacity of TPS3R, Composting and Waste Bank.
- adding an environmentally friendly ORC turbine hydro-drive incinerator with a large capacity.

Reducing the amount of waste generation requires changes in people's behavior and the production process of goods and food, so this model is not simulated. So what will be simulated in this model is for the scenario:

- implementation of environmentally friendly ORC turbine hydro-drive incinerators
- increased processing capacity of TPS3R, composting and Waste Bank

From several simulated scenarios, the results will be obtained from the application of several environmentally friendly ORC turbine hydrodrive incinerators as well as increasing the processing capacity of TPS3R, composting, and Waste Bank. Limited land in urban areas results in an increase in waste processing capacity through TPS3R, composting and Waste Banks being limited so that when a waste emergency occurs, the application of environmentally friendly thermal technology is one solution. From the simulation results, it can also be calculated the amount of electricity generated by the ORC turbine hydrodrive incinerator and the amount of CO_2e emissions reduced.

3.5 Verification and validation

This model has been simulated using Powersim software and runs without any errors in units or formulations.The model is well-verified.

Meanwhile, validation was carried out using factual data as a statistical measure, including data on the population, the amount of waste generated by the population, and the amount of waste sent to Galuga WFP from the previous year. The MAPE results ranged from 1.85-8.32% (tolerance <10%) (see Table 3.), which means that the model data is appropriate and accurate, and the model can be used.

Table 3. Model subsystem validation.

Year	Data	Simulation	Result (%)	Description
Population				
2018	1,096,828	1,029,080	6.18	Total 12.70 MAPE: 2.54 (Very appropriate)
2019	1,048,610	1,049,662	0.10	
2020	1,043,070	1,070,655	2.64	
2021	1,052,359	1,092,068	3.77	
2022	1,114,018	1,113,909	0.01	
Waste Generation				
2018	226,581.00	229,691	1.37	Total 9.27 MAPE: 1.85 (Very appropriate)
2019	240,205.33	239,785	0.18	
2020	245,922.33	250,116	1.71	
2021	245,922.33	260,698	6.01	
2022	271,727.57	271,705	0.01	
Waste sent to Galuga WFP				
2018	179,528	157,985	179,528	Total 41.62 MAPE: 8.32 (Appropriate)
2019	184,916	166,995	184,916	
2020	195,540	176,226	195,540	
2021	206,164	185,690	206,164	
2022	195,787	195,551	195,787	

3.6 Result of scenario analysis

After the system dynamics model is declared valid with the results of the verification and validation tests above. Then a policy implementation scenario was developed to achieve the desired goals and prevent problems that might occur in the years ahead, namely reducing the amount of waste sent to the Galuga WFP to extend the life of the WFP and make the WFP sustainable. Even gradually until no more waste is sent to WFPs in 2050 as the goal of the Bogor city government. And also reduces the amount of CO_2e emissions from the reduction in the amount of waste sent to WFPs.

In addition, using a hydrodrive incinerator combined with ORC turbine technology can generate electrical energy. To determine the improvements that will be achieved, this model is used in the formulation of implementation scenarios. To achieve the desired goals and prevent problems that may occur in future years with the possibility of various policies.

The scenarios carried out in this research are to increase the waste reduction capacity, namely:

- Running existing conditions (Business as Usual/BAU): scenario-0

- Increase the reduction capacity of composter, TPS3R and waste bank (scenario 1a - 1c)
- Adding ORC turbine Hydrodrive Incinerator (scenario 2a - 2c)
- Combination of adding ORC turbine Hydrodrive Incinerator and increasing the reduction capacity of the composter, TPS3R, and waste bank (scenario 3a - 3c)

The simulation scenarios carried out on this research model can be seen in Table 4.

Table 4. Simulation scenario.

Scenario	Variables	Description
0	BAU. Composter, TPS3R, and Waste Bank grow 1% per year without Hydrodive ORC	No ORC Hydrodrive Incinerator
1a	Composter, TPS3R, and Waste Bank grow 2% per year from 2023 Without Hydrodive ORC	No ORC Hydrodrive Incinerator
1b	Composter, TPS3R, and Waste Bank grew 5% per year since 2023 Without Hydrodive ORC	No ORC Hydrodrive Incinerator
1c	Composter, TPS3R, and Waste Bank grew 10% per year since 2023 Without Hydrodive ORC	No ORC Hydrodrive Incinerator
2a	2 ORC incinerator units added every 5 years since 2024 Composter, TPS3R, and Waste Bank grow 1% per year	By ORC Hydrodrive Incinerator
2b	4 ORC incinerator units added every 5 years since 2024 Composter, TPS3R, and Waste Bank grow 1% per year	By ORC Hydrodrive Incinerator
2c	Added ORC incinerator unit: - 5 units in 2024, - 5 units in 2026, - 6 units in 2028, - 6 units in 2030, and - 6 units in 2033 Composter, TPS3R, and Waste Bank grow 1% per year	By ORC Hydrodrive Incinerator
3a	5 ORC incinerator units added every 5 years since 2024 Composter, TPS3R, and Waste Bank grow 1% per year	Combination
3b	Added ORC incinerator unit: - 5 units in 2024, - 6 units in 2026, - 6 units in 2028, and - 6 units in 2030 Composter, TPS3R, and Waste Bank grow 2% per year	Combination
3c	Added ORC incinerator unit: - 5 units in 2024, - 6 units in 2026, - 6 units in 2028, and - 6 units in 2030 Composter, TPS3R, and Waste Bank grow 3% per year	Combination

The simulation results of the BAU scenario (scenario-0) can be seen in Fig. 4 - 5. The simulation results of the BAU scenario (scenario-0) show that the life of the WFP is only until 2028 if the existing waste reduction processing capacity is only with 1% capacity growth each year. Because the waste sent to the WFP cannot be accommodated by the WFP the waste can no longer enter the WFP and the waste becomes unmanaged. Starting in 2028, the amount of unmanaged waste will increase significantly. After 2028 the waste that can enter the WFP is only the amount of waste reduction capability that the WFP has naturally, which is naturally degraded. So a policy is needed to prevent this problem from occurring, namely with a policy to increase the waste reduction capacity before being sent to WFP. Because otherwise, it will require new land to create a new WFP.

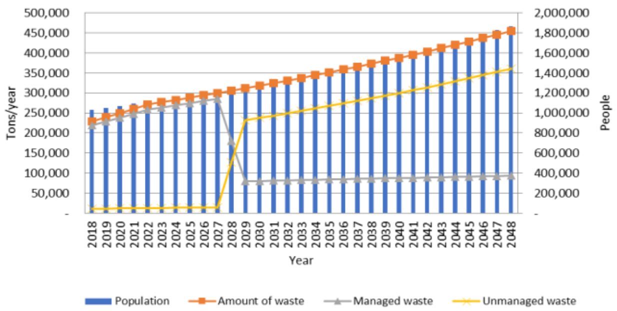

Fig. 4: Population, waste generation, and management according to scenario-0.

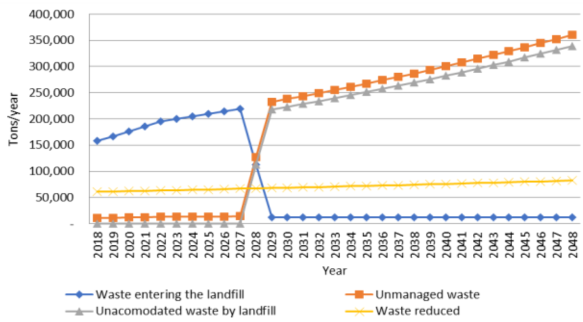

Fig. 5: Waste flow according to scenario-0.

The results of the scenario simulations can be seen in Table 5 and Fig. 6 – 11.

From the simulation results, it can be seen that:

- Scenario-1c: If the growth of TPS3R, Composter, and Waste Bank facilities can be increased by 10% every year, it can reduce waste entering the WFP. In addition, the economic value that can be utilized is quite large and the distribution is wider because it involves many communities. However, various obstacles faced are the difficulty of land, requiring community participation and community awareness, so it takes a long time, socialization, and public learning. In the long term, community-based waste management activities are very promising. But for Bogor city, this is difficult to achieve because there is no land and the growth of TPS3R, Composter, and Waste Bank is also very small.

Table 5. Simulation results of scenarios.

Scenario Numbers	WFP lifespan up to year	Accumulated Waste Reduction 2018-2048 (tons)	Accumulated CO_2e Emission Reduction 2018-2048 (tons)	Accumulated Electricity generated Year 2018-2048 (tons) (kWh)
0	2028	2,118,757	1,800,944	-
1a	2028	2,341,722	1,990,464	-
1b	2028	3,252,108	2,764,292	-
1c	2028	6,096,736	5,182,226	-
2a	2028	3,522,757	2,994,344	37,440,000
2b	2029	4,926,757	4,187,744	74,880,000
2c	Sustainability	7,734,757	6,574,544	149,760,000
3a	2029	5,628,757	4,784,444	93,600,000
3b	2045	7,277,322	6,185,724	131,616,000
3c	Sustainability	7,536,250	6,405,813	131,616,000

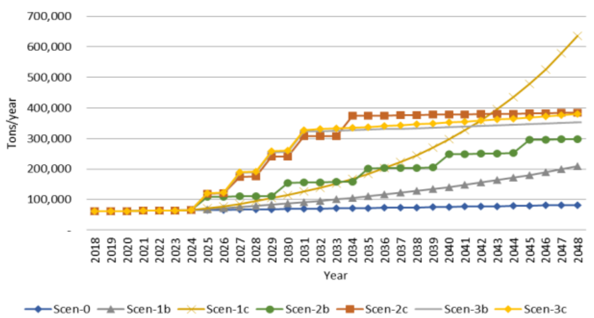

Fig. 6: Waste reduction for various scenarios.

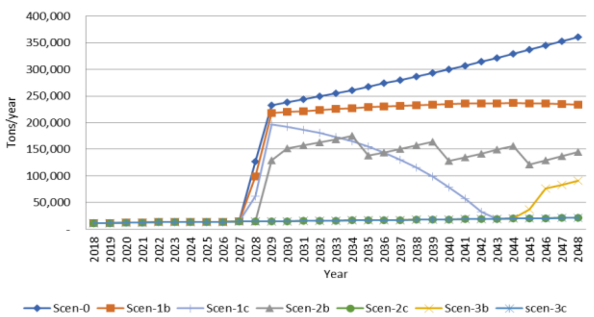

Fig. 7: Unmanaged waste across scenarios.

- Scenario-2a, 2b, 2c, 3a, 3b, 3c: If there is an increase in the amount of waste where existing processing facilities are difficult to upgrade due to various constraints, especially land and community rejection, then the thermal process approach is the solution, which can process waste in a short time and does not require large land. The problems faced are exhaust emissions and a lot of lost economic value. To overcome this, an environmentally friendly Hydrodrive Incinerator has been developed, because it does not use fossil fuels and has low emissions. To capture the lost economic value, the heat generated can be converted to electricity. ORC turbines are very suitable (although still in the research stage) because they can produce electricity with lower heat when compared to conventional turbines. Although the investment is quite expensive, the waste emergency condition can be overcome with the application of this technology.

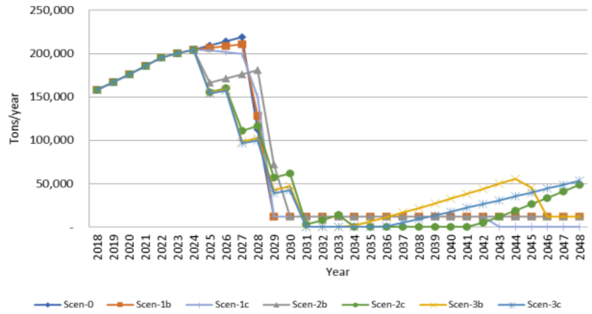

Fig. 8: Waste entering the WFP under various scenarios.

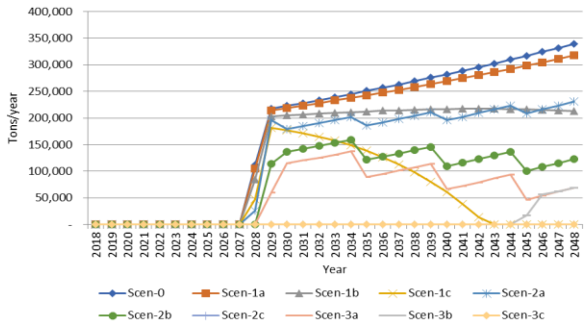

Fig. 9: Waste not collected in the WFP.

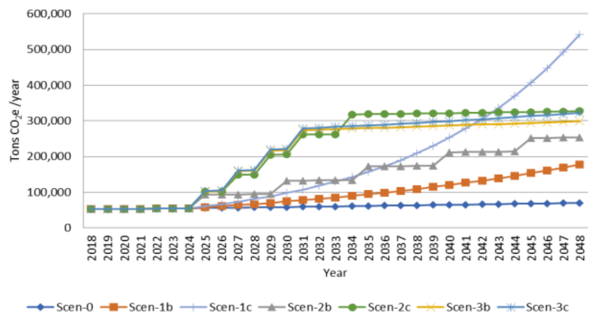

Fig. 10: Emissions reduction (CO_2e) various scenarios.

- The simulation results show that the life of the WFP is only around 2028 if the existing waste processing capacity only increases by 1% (scenario-0). WFP management will also not be sustainable even though the existing waste processing capacity increases every year (scenario-1a -1c) this will also be difficult to do because of land acquisition constraints and community rejection, even existing processing facilities such as TPS3R have received many community protests and the number has never increased, even reduced. The same applies to biological processing facilities (compost). RDF and animal feed processing are developing, but their development still requires time and community learning. This makes the growth of processing capacity by 10% very difficult because it must involve many people and requires the right land and location so as not to disturb the community.

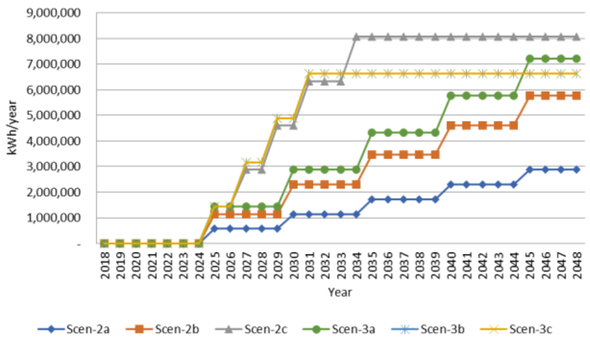

Fig. 11: Electricity generated by various scenarios.

- To overcome the high increase in waste generation due to high population growth rates (2% per year), thermal technology (incinerators) is needed. If using existing waste processing facilities with 1% capacity growth each year, the WFP will only last until 2028, after which it will be full and require new land.
- To ensure the sustainability of the WFP, the waste reduction capacity before entering the WFP must be increased. From the results of the scenario-2c simulation carried out with the growth of existing facilities by 1% per year, an additional 5 ORC incinerator units are needed in 2024, 5 ORC incinerator units in 2026, 6 ORC incinerator units in 2028, 6 ORC incinerator units in 2030 and 6 ORC incinerator units in 2033, in this scenario 2c in 2048 the results are: waste reduction reached 384,498 tons/year, CO_2e emission reduction of 326,823 tons/year with electricity generated 8.06 million kWh. 06 million kWh. And the WFP becomes sustainable.
- Or with scenario-3c, namely adding 5 ORC incinerator units in 2024, 6 ORC incinerator units in 2026, 6 ORC incinerator units in 2028, and 6 ORC incinerator units in 2030 and the existing waste processing capacity must be increased by 3 percent each year. In the results of this scenario in 2048, namely: waste reduction reached 379,835 tons/year, reduction of CO_2e emissions by 322,860 tons/year with electricity generated 6.62 million kWh. And the WFP becomes sustainable.

From the simulation results of the scenarios above, scenario scenario 2c will be selected to be recommended to be applied to waste management in the city of Bogor. In addition to the conditions that are by the city of Bogor, the simulation results of scenario scenario 2c are also able to make the WFP sustainable. For 30 years of simulation, the accumulated amount of waste reduction to WFP is 7,734,757 tons, the accumulated amount of CO_2e gas emission reduction is 6,574,544 tons and the accumulated amount of electricity generated is 149,760,000 kWh. Land expansion for WFP is not necessary, so this is supporting the low-carbon development initiated by The Government of Indonesia.

The increasing amount of waste in Bogor City and limited WFP site, so in addition to optimizing existing processes, it is necessary to support it with new technology that can reduce the amount of waste sent to the WTP and the waste to energy can be applied. So this application of hydro-drive incinerator technology and ORC turbines does not disrupt the stability of existing waste management infrastructure, and it will even increase the effectiveness of waste management in Bogor City and extend the lifespan of existing WFP.

4. Conclusion and recommendation

The amount of waste in Bogor City continues to increase due to population growth. Waste management must be managed with proper planning for decades to come. This dynamic system model has been simulated with various scenarios in a period from 2018-2048. The simulation results of the dynamic system model of the projected amount of waste reduction sent to the WFP for ske-0 or BAU show that the Galuga WFP will be full in 2028 where the waste can no longer be accommodated in the WFP and becomes unmanaged waste. So there needs to be a policy to prevent this problem from happening. For the sustainability of the Galuga WFP, several scenarios have been simulated, and from the simulation results it is recommended that scen-2c be implemented. Because it can make the Galuga WFP sustainable. The scenario scen-2c is waste processing with the addition of 5 (ORC turbine and hydrodrive incinerator) units in 2024, 5 units in 2026, 6 units in 2028, units in 2030, and 6 units in 2033; Composter, TPS3R, and Waste Bank grow 1% per year. From the results of this modeling, it is obtained that the accumulated amount of waste reduction sent to the WFP until 2048 is 7,734,757 tons of waste, for the electricity generated is 149,760,000 Kwh, while for the reduction of CO_2e gas emissions is 6,574,544 tons of CO_2e. In addition to the Galuga WFP being sustainable, it also reduces CO_2e gas emissions and produces electrical energy that can be utilized by the community.

The increasing amount of waste and limited WFP site, so in addition to optimizing existing processes, it is necessary to support it with waste reduce technology. So this application of hydro-drive incinerator technology and ORC turbines will even increase the effectiveness of waste management in Bogor City and extend the life of existing WFP. This will support national policies to achieve the SDGs, low-carbon development initiatives, and Indonesia's Net Zero Emission by 2060.

This waste management model with hydro-drive incinerators and ORC turbines can be the best practice for waste management in other urban in Indonesia. However, its implementation requires modifications that are adjusted to the conditions of the city, especially the socio-economic aspects and existing waste management schemes

Acknowledgments

The authors thank the Regional Development Planning Agency and the Environment Office - Bogor City for the data, information, and discussion.

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