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Landfill design based on methane gas emission estimates at Jatibarang Final Disposal Site (TPA) in Semarang City using LandGEM 3.03 and its potential utilization as an energy source

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ABSTRACT

This study aims to analyze the landfill design based on the estimated methane gas emissions at the Jatibarang Landfill, Semarang City, using the Landfill Gas Emissions Model (LandGEM) software version 3.03 and evaluate its potential utilization as an energy source. The study uses a quantitative approach utilizing mathematical modeling to estimate the estimated gas emissions from the landfill. The results show that the potential for electrical energy that can be generated from landfills is high enough to be recommended for management using the concept of Waste to Energy (WTE) into electrical energy. The recommendation that will be discussed is the management of methanogas emissions by being used as electrical energy, emphasizing infrastructure improvements for optimal energy production and reducing greenhouse gas emissions. This study could also incorporate real-time monitoring of gas emissions and energy production to better understand the dynamics of waste decomposition and the benefits of electricity generated from waste could foster community support for PLTSa initiatives.

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INTRODUCTION

Waste management activities are a sustainable development goal in the 12th pillar of the SDGs, namely responsible consumption and production. Achieving economic growth and sustainable development means we must recognise the importance of reducing our ecological footprint by changing the way we produce and consume food and other resources. Responsible consumption and production guarantee sustainable production and consumption patterns It is explained that by 2030, substantially reduce waste production through prevention, reduction, recycling and reuse (Subekti et al., 2023).

The increase in the number of people in an area is also followed by an increase in economic growth, an increase in settlement facilities and the existence of various social activities of the community resulting in an increase in the volume of waste every day. The increase in the volume of waste produced every day results in the need for land area as a waste shelter at each Final Processing Site (TPA). Conditions like this have resulted in an increase in piles of garbage that pile up in temporary garbage shelters. According to data from the Ministry of Environment and Forestry (MoEF), the first largest volume of waste, which is 37.3% of waste comes from household activities, then the second largest is sourced from traditional market waste of 16.4%, followed by waste sources from the region at 15.9% and other waste at 14.6% (Subekti et al., 2023).

According to the National Waste Management Information System (Kementerian Lingkungan Hidup dan Kehutanan, 2020), Indonesia is one of the largest waste producing countries in the world, while the largest waste producers come from urban communities. Waste sources are usually obtained from household waste, agricultural waste, waste from markets, office waste, hospital waste, school waste, industrial waste, building construction waste, livestock waste and fishery waste. With the increasing progress of an area, the amount of waste production rate is often not proportional to the process of dealing with it, so it is necessary to think about solving the waste problem. This condition has an influence on various sectors related to meeting the needs of the population, one of which is the provision of urban infrastructure including waste facilities and infrastructure (Subekti et al., 2023).

According to Law Number 18 of 2008, it is necessary to implement waste reduction and utilization through the 3R program, namely Reduce (change consumptive lifestyle), Reuse (reuse materials that have the potential to become waste and refill materials) and Recycle (recycle through composting, recycling, waste to energy) and others. And strengthened by Presidential Regulation Number 35 of 2018 concerning the Acceleration of the Construction of Waste Processing Plants into Electrical Energy Based on Environmentally Friendly Technology. Waste processing is part of waste management and Law Number 18 of 2008 is defined as the process of changing the shape of waste by changing the characteristics, composition, and amount of waste. Waste processing is an activity intended to reduce the amount of waste, in addition to utilizing the value that is still contained in the waste itself (recycled materials, other products and energy). This is emphasized in Government Regulation No. 81 of 2012 that in waste processing, in addition to compaction, composting and recycling can be through energy recycling (Subekti et al., 2023).

Waste management encompasses five key aspects: pollution prevention, waste minimization, recycling, treatment, and disposal. In Indonesia, petroleum dominated energy demand in 2018, with projections indicating that by 2050, petroleum and electrical energy demand will be nearly equal across industrial (80%), commercial (60-70%), and household (60%) sectors, while New Renewable Energy (NRE) constituted only 3-5% of the energy mix. Although the supply of NRE is expected to balance with natural gas, coal remains the primary source for electrical energy, with geothermal and hydropower leading in NRE production. Waste as a source of NRE is currently less utilized compared to biomass, but projections suggest a future reliance on solar power and biomass. The decomposition of waste in landfills typically occurs through a facultative process, transitioning from aerobic to anaerobic conditions, ultimately producing biogas and resulting in stabilized material once decomposition is complete. Landfills are said to be stable when leachate no longer contains harmful pollutants, gas production can be negligible, and there has been a decrease in waste accumulations (Zaman & Priyambada, 2007).

Anaerobic activities or fermentation derived from organic matter from living materials including manure, domestic waste, biodegradable waste or any organic waste that is biodegradable in anaerobic conditions will produce a gas called biogas. The composition and content of biogas elements vary depending on the origin of the anaerobic process. The gas produced from organic waste in the landfill area contains approximately 50% methane gas. For a controlled landfill system, it can produce biogas with 55-75% methane gas (CH4), the content of biogas elements from anaerobic processes. Methane gas (CH4), which is the main component of biogas, is a useful fuel, which is why biogas can be used for lighting, cooking, and driving machines (Subekti et al., 2023). Landfill gas (LFG) is produced by microbes during the fermentation of organic matter in anaerobic conditions, influenced by temperature, humidity, and acidity. This gas, primarily composed of methane, is a crucial fuel for electricity generation, as it burns cleaner than other fossil fuels, resulting in lower carbon dioxide emissions per unit of heat. Methane, when compressed, serves as a more environmentally friendly vehicle fuel compared to gasoline and diesel. In sanitary landfills, the anaerobic decomposition of organic waste begins once the waste is compacted and covered, preventing the entry of oxygen. Methane gas will form after a period of 6-12 months when the landfill is closed or the waste is in anaerobic conditions (Hapsari & Wahyuni, 2020).

In the process of estimating the level of emissions from the total gas produced in landfills in landfills, an automatic estimation tool published by the U.S. Environmental Proctection Agency (EPA) based on Microsoft Excel software on MS-Office can be used, namely LandGEM. LandGEM is based on the first-order decomposition rate equation to measure emissions from the decomposition of waste piled up in municipal solid waste (MSW). The software provides a relatively simple approach to estimating landfill gas emissions. The default model is based on empirical data from landfills in the US. Field test data can also be used in place of the default model if available. LandGEM is based on the first-order decomposition rate equation to measure emissions from the decomposition of waste piled up in municipal waste dumps (MSW). The software provides a relatively simple approach to estimating landfill gas emissions. The default model is based on empirical data from landfills in the US. Field test data can also be used in place of the default model if available (U.S. Environmental Protection Agency, 2020).

This study aims to analyze the landfill design based on the estimated methane gas emissions at the Jatibarang Landfill, Semarang City using the Landfill Gas Emissions Model (LandGEM) software version 3.03 and evaluate its potential utilization as an energy source. The research contribution of this study lies in its comprehensive analysis of landfill design through the estimation of methane gas emissions at the Jatibarang Landfill in Semarang City, utilizing the Landfill Gas Emissions Model (LandGEM) software version 3.03. By evaluating the potential utilization of these emissions as an energy source, the study not only enhances the understanding of methane management in landfills but also contributes to sustainable energy solutions and waste management practices, potentially informing policy and operational strategies in similar contexts.

The current study analyzes methane gas emissions and their potential for energy generation at the Jatibarang Landfill using the LandGEM software, focusing on infrastructure improvements for effective

methane management. In contrast, the research by Soleh et al. (2020) emphasizes the economic feasibility and cost-benefit analysis of waste-to-energy (WTE) technologies at the same landfill. While both studies address the potential of municipal solid waste, the current study fills a research gap by integrating detailed emissions modeling with energy potential analysis, providing a more comprehensive approach to evaluating WTE viability. Its novelty lies in the application of LandGEM for emission estimation and the proposal of specific recommendations for optimizing energy production, along with an emphasis on real-time monitoring of gas emissions.

METHOD

This study employs a quantitative approach utilizing mathematical modeling to estimate methane gas emissions from the Jatibarang Final Processing Site (TPA). The estimation process is conducted using the Landfill Gas Emissions Model (LandGEM) software version 3.03, which provides a framework for assessing the emissions generated by the landfill over time.

Data collection for the study is based on secondary sources, including demographic and waste management statistics. Key data points include the population of Semarang City sourced from the Central Statistics Agency (BPS), the volume of waste entering the Jatibarang Landfill obtained from the National Waste Management Information System (SIPSN), and LandGEM default parameter values (such as k, L0, and gas collection efficiency) derived from relevant literature.

The population projection utilizes the geometric formula:

$$P_n = P_0 (1 + r)^n$$

where P_n is the projected population after n years, P_0 is the initial population, rr is the population growth rate, and nn is the number of years. Projected waste generation is calculated based on per capita waste data from 2022, multiplied by the projected population to estimate total waste generation annually. Gas emission modeling is performed using LandGEM version 3.03, with inputs including the organic waste composition (assumed to be 61% of total waste), and parameters such as k=0.18k=0.18 (for a hot and wet climate) and L0=60 m3/MgL0=60m3/Mg (methane production potential). The annual methane emissions are calculated with the equation:

$$QCH4= \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_i}{10}\right) e^{-ktij}.$$

The landfill is designed for a 30-year operational period (2024-2054) with four landfill cells added every five years, each having equal capacity. Waste distribution is proportionally based on incoming waste projections, and emissions are calculated for each cell individually as well as cumulatively. To assess the potential for energy generation, methane conversion to electrical energy is calculated using the formula:

$$Ep = \frac{QCH_4 \; x \; \lambda CH_4 \; x \; \eta \; x \; LHVCH_4 \; x \; 0.9}{3.6}$$

where λ_{CH4} represents methane collection efficiency (75%), LHV_{CH4} is the lowest calorific value of methane (37.2 MJ/m³), and ηη is the electricity conversion efficiency (35%). The study also evaluates sustainability through economic benefits from energy production and environmental impacts from reduced greenhouse gas emissions. Finally, recommendations for landfill management will be prepared, emphasizing infrastructure improvements for optimal methane collection and utilization.

RESULTS AND DISCUSSION

Landfill Flue Gases (LFG) Emitted from Jatibarang Landfill

Activity The purpose of making this assignment paper is to design the utilization of Landfill Gas (LFG) produced from Landfill at the Jatibarang Landfill, Semarang City in the operational design range of the next 30 years from 2024, and it is planned to add 4 Landfill cells every 5 years per cell with the same capacity area and the same operational range, which is 30 years from the first year of operation.

Composition of Landfill Gas (LFG)

Landfill Gas (LFG) is produced from biological and chemical processes that occur when waste is buried in landfills. The main components of LFG are carbon dioxide (40–50%) and methane (50–60%) (Aghdam et al., 2019). Many studies have been conducted to estimate the amount of gas production from municipal landfills. So, various models have been designed to calculate greenhouse gas emissions, oxidation, and also landfill gas production. In terms of modeling landfill processes, the importance of local factors, such as waste composition, disposal, and protection systems against potential impacts, led to the development of models used for various landfill facilities.

Table 1. Percentage of LFG Constituent Gases

No	LFG Constituent Gases	Chemical Formula	Content Percentage
1	Methane	Q4	40 – 60 %
2	Carbon dioxide	CO2	25 – 50 %
3	Nitrogen	N2	3 – 15%
4	Oxygen	O2	0 – 4%
5	Hidrogen	H2	0 – 1 %
6	Argon	Ar	0 – 4%
7	Hydrogen sulfide	*H2S*	0-200 ppm
8	Chlorine	Cl	0-200 ppm
9	Fluerine	F	0-200 ppm

Source: Garcilasso, 2011

The table above shows that the percentage of gases that make up LFG, it can be seen that the largest gas content contained in LFG is methane of 45 – 60 % carbon dioxide content of 25 – 50%. Both methane and carbon dioxide gases have a role in increasing the warming of the earth's temperature and are categorized as greenhouse gases (GHGs). Landfill gas produced at landfills will be dangerous if not managed and controlled properly. Landfill Gas or LFG is a gas produced by microbes when organic matter undergoes a fermentation process in an anaerobic state that is suitable in terms of temperature, humidity, and acidity.

The table below shows the percentage of the constituent gases of LFG, and it can be seen that the most significant gas content contained in LFG is methane at 50% to 70% and followed by carbon dioxide at 30% to 40%. Both methane and carbon dioxide have a role in increasing global warming and are categorized as greenhouse gases (GHGs). Landfill gas produced in landfills will be dangerous if not managed and controlled properly. The methane gas content in LFG is a flammable gas so that the risk of explosion around the landfill location is very high (Soleh et al., 2020).

Table 2. Composition of LFG gas

LFG Composition	Chemical Formulation	Percentage (%)
Methane	CH4	50 – 70
Carbon Dioxide	CO2	30 – 40
Hidrogen	H2	5 – 10
Nitrogen	N2	1 – 2
Nitrous Oxide	N2O	0,3
Hydrogen Sulfide	H2S	Very low

Source: Soleh et al. (2020)

Estimation of Gas Emissions from the Jatibarang Landfill Landfill with the Landfill Gas Emissions Model (LandGEM) Application Version 3.03

In calculating the estimated gas emissions from the landfill from the Jatibarang landfill, the Landfill Gas Emissions Model (LandGEM) version 3.03 application is used as an estimation tool. LandGEM is specifically designed to analyze gas emissions from landfills. Using an excel mathematical model, LandGEM can estimate the amount and type of gas produced from waste decay activities in landfills. The main advantage of LandGEM is its ability to provide accurate estimates of gas emissions such as methane and carbon dioxide from certain landfills (Nurjaya & Rachmanto, 2023).

To calculate the potential for methane gas to be produced from the landfill to be designed, using data on the amount of waste entering the landfill is calculated using initial data sourced from the National Waste Management Information System (Kementerian Lingkungan Hidup dan Kehutanan, 2020). This is with the justification that several journals also use data from the same source, namely SIPSN, as conveyed in their journals by Harjanti & Anggraini (2020) and Subekti et al. (2023).

Projected Waste Generation Entering the Jatibarang Landfill

To design the utilization of Landfill Gas (LFG) produced from Landfill at the Jatibarang Landfill, Semarang City in the operational design range for the next 30 years from 2024 using Microsoft Excel software on MS-Office, namely LandGEM. In the need for data, projected data on waste generation that enters the Jatibarang Landfill from 2024 onwards is needed. The calculation of the projection is based on data on the population of Semarang city in that year multiplied by the amount of waste generated per person per year. Meanwhile, the number of people in Semarang city in a given year is calculated based on projections using population growth rate data.

Based on Semarang city SIPSN data (2024), the data on waste entering the landfill in 2022 is 308,050.51 tons/year. If calculated based on the number of people in the city of Semarang in 2022 is 1,659,975 people, then the generation of tons/person/year of waste in the city of Semarang that enters the landfill in 2022 is:

Semarang city waste generated in landfill in 2022 = $\frac{308.050{,}51\ tonne/year}{1.659.975\ people}$ = 185,575 kg/person/year



Figure 1. Semarang population growth rate, 2018 – 2022
Source: https://semarangkota.bps.go.id/

Based on data on the population growth rate of Semarang city in 2018 – 2022 (figure 13) is as follows:

Table 3. The population growth rate of Semarang city in 2018 – 2022

Year	Population growth rate (%)
2018	0,51
2019	1,57
2020	0,59
2021	0,25
2022	0,21

Source: https://semarangkota.bps.go.id/

The formula used to calculate the population projection is arithmetic, geometric, and exponential formulas. We can use this arithmetic formula if we consider that the number of people every year is always the same. The formula is as follows:

$$Pn = P0 \{1 + (r.n)\}$$

Information:
Pn = Number of population after the next n years
P0 = Number of inhabitants in the first year
r = Population growth figure
n = Period in years

In addition, it can also use the Geometric formula. The calculation of the population with this formula uses the basis of population growth compound interest (flowering interest). The formula is:

$$Pn = P0\ (1 + r)^n$$

Information:
Pn = Number of population after the next n years
P0 = Number of inhabitants in the first year
r = Population growth figure
n = Period in years

Finally, you can use an exponential formula. The use of this formula is when the population growth is constant or continuous every day. Here's the formula:

$$Pn = P0er.n$$

Information:
Pn = Number of population after the next n years
P0 = Number of inhabitants in the first year.
r = Population growth figure.
n = Period of time in years.
e = Exponential number (2.7182818)

In this study, the Geometric formula is used to calculate the projected population from 2024 and continue to the following years. The results can be seen in appendix 1 (projection of the population of the city of Semarang in 2024 – 2100 based on the Geometric formula). Based on 2022 data for waste generation per person in the city of Semarang of 185,575 kg/person/year is assumed to be constant, it will be possible to obtain a projection of waste generation entering the landfill from 2024.

Estimated Gas Emissions from Jatibarang Landfill

Modelling using LandGEM was carried out based on an estimate of the total waste that came in each year, then an analysis of gas generation (total landfill gas, methane, carbon dioxide and Non Methane Organic Compound / NMOC) was carried out in the Jatibarang landfill area, which functioned until the year of the landfill's closure. The LandGEM spreadsheet is intended to be used to analyze the rate of gas emission formation in the Jatibarang landfill area. LandGEM's standard selection is used for model parameters for analytical needs, which are then adjusted to the circumstances of the study site.

The LandGEM model uses equations based on first-order decomposition to estimate gas emissions according to a specified time period. Two important parameters used in modeling LFG generation based on first-order equations are the methane production rate constant, k ($^{yr-1}$) and methane production potential, L0 (m3/Mg) (Fallahizadeh et al., 2019).

LandGEM Modeling Equations:

$QCH4 = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_i}{10}\right) e^{-ktij}$

Where:
QCH4 = CH_4 emissions produced annually (m3/year)
L0 = Potential methane production capacity (m3/Megagram)
k = Methane gas production rate ($^{year-1}$)
t = Landfill age (years)
Mi = amount of waste that goes to the landfill in year i (Megagram)
i = 1-year operational
Note: Mg represents one megagram, however 1 Mg is equivalent to 1 metric ton

The value of k and L0 depends on the local climatic conditions and the composition of the waste. The value of k, determines the level of methane generation in the landfill. If the unit used is in per year, and describes the level of waste disposal in landfills and producing biogas. The value of k is higher, causing the acceleration of total methane generation in landfills to increase and decrease along with the landfill closure year. The value of k is influenced by moisture content in garbage (moisture content), availability of nutrients for methane-producing bacteria, Ph, and temperature. Different types of waste can give different k values as a result of different decay rates. The value of the potential for methane generation (Lo) depends on the type or waste that is disposed of in the landfill. The greater the biodegradable organic carbon content in the waste that is disposed of, the greater the Lo value.

In this research conducted at the Jatibarang Landfill, using user-specific k and L0 values from Thailand with the consideration that in Indonesia there is no reference to the user-specific value and the country's geographical conditions are similar to Thailand. The default value k is based on the assumption of the landfill location, which is "Hot and Wet". The recommended k-value developed for Thailand is assumed to be "Hot and Wet" which is 0.18. And the recommended L0 value in Thailand is 60 m3/Mg. The default model parameters used in the LandGEM simulation in this study are the percentage of methane content in landfill gas (Methane content % by volume), which is assumed to be 50% because the composition of landfill gas for methane is at a vulnerable 40-60% and for the concentration of NMOC (Non Methane Organic Compound) according to the defaulft LandGEM application refers to CAA – 4,000 (ppmv as hexane).

Meanwhile, the projected results of waste generation that enters the landfill from 2024 to 2054 (according to the design of the Jatibarang landfill, which is 30 years) as an input to the projection of total waste every year at LandGEM. In this study, the input of waste that enters the landfill is only for the percentage composition of the amount of organic waste. This is because this research is to get a more specific estimate by focusing on the methane gas produced for its potential use as an energy source. The percentage of organic waste composition assumed in this study is for food waste with a rounding value from the average of the last 3 years, which is 61%. The input results of the LandGEM Jatibarang Landfill Semarang City period for the

Landfill scenario of 1 cell design with an operational period of 2024 – 2054 can be seen in Appendix 3, as well as the input for the scenario with a 4-cell Lanffill design, namely cell 1 for the period 2024 – 2054, cell 2 for the period 2030 – 2060, cell 3 for the period 2035 – 2065 and cell 4 for the period 2040 – 2070 in Appendix 4, 5, 6 and 7. In this study, the input of waste that enters the landfill is only for the percentage composition of the amount of organic waste. This is because this research focuses on the methane gas produced for its potential use as an energy source.

The calculation of the total gas emissions generated from the design of the landfill at the Jatibarang Landfill for the operating period of 2024 to 2054 using LandGEM software produces gas emissions consisting of total landfill gas, CH4 gas, CO2 gas and non-methane organic compounds (NMOC).

Table 4. Total gas emissions generated from the design of the Landfill at the Jatibarang Landfill for the operating period 2024 to 2054 using LandGEM ver. 3.03

Year	Total landfill gas		Methane		Carbon dioxide		NMOC	
	(Mg/year)	(m3/year)	(Mg/year)	(m3/year)	(Mg/year)	(m3/year)	(Mg/year)	(m3/year)
2024	0	0	0	0	0	0	0	0
2025	4.700	3.763.823	1.256	1.881.911	3.445	1.881.911	54	15.055
2026	8.636	6.915.536	2.307	3.457.768	6.329	3.457.768	99	27.662
2027	11.934	9.555.988	3.188	4.777.994	8.746	4.777.994	137	38.224
2028	14.698	11.769.417	3.926	5.884.708	10.772	5.884.708	169	47.078
2029	17.017	13.626.182	4.545	6.813.091	12.471	6.813.091	195	54.505
2030	18.963	15.185.053	5.065	7.592.526	13.898	7.592.526	218	60.740
2031	20.599	16.495.119	5.502	8.247.559	15.097	8.247.559	237	65.980
2032	21.976	17.597.382	5.870	8.798.691	16.106	8.798.691	252	70.390
2033	23.136	18.526.091	6.180	9.263.045	16.956	9.263.045	266	74.104
2034	24.115	19.309.851	6.441	9.654.925	17.673	9.654.925	277	77.239
2035	24.942	19.972.557	6.662	9.986.279	18.280	9.986.279	286	79.890
2036	25.644	20.534.168	6.850	10.267.084	18.794	10.267.084	294	82.137
2037	26.239	21.011.353	7.009	10.505.676	19.231	10.505.676	301	84.045
2038	26.747	21.418.037	7.145	10.709.018	19.603	10.709.018	307	85.672
2039	27.182	21.765.850	7.261	10.882.925	19.921	10.882.925	312	87.063
2040	27.555	22.064.508	7.360	11.032.254	20.195	11.032.254	316	88.258
2041	27.876	22.322.125	7.446	11.161.063	20.430	11.161.063	320	89.289
2042	28.155	22.545.479	7.521	11.272.739	20.635	11.272.739	323	90.182
2043	28.399	22.740.230	7.586	11.370.115	20.813	11.370.115	326	90.961
2044	28.612	22.911.108	7.643	11.455.554	20.969	11.455.554	328	91.644
2045	28.800	23.062.063	7.693	11.531.032	21.108	11.531.032	331	92.248
2046	28.968	23.196.394	7.738	11.598.197	21.230	11.598.197	333	92.786
2047	29.119	23.316.857	7.778	11.658.428	21.341	11.658.428	334	93.267
2048	29.255	23.425.753	7.814	11.712.876	21.440	11.712.876	336	93.703
2049	29.379	23.525.005	7.847	11.762.503	21.531	11.762.503	337	94.100
2050	29.492	23.616.220	7.878	11.808.110	21.615	11.808.110	339	94.465
2051	29.598	23.700.739	7.906	11.850.369	21.692	11.850.369	340	94.803
2052	29.697	23.779.682	7.932	11.889.841	21.764	11.889.841	341	95.119
2053	29.789	23.853.985	7.957	11.926.993	21.832	11.926.993	342	95.416
2054	29.877	23.924.431	7.981	11.962.215	21.897	11.962.215	343	95.698
2055	29.961	23.991.672	8.003	11.995.836	21.958	11.995.836	344	95.967
2056	25.026	20.039.529	6.685	10.019.764	18.341	10.019.764	287	80.158

The figure below is a graph of gas emissions from Landfill modeling at the Jatibarang Landfill for the 2024 to 2054 operating period using LandGEM ver. 3.03.

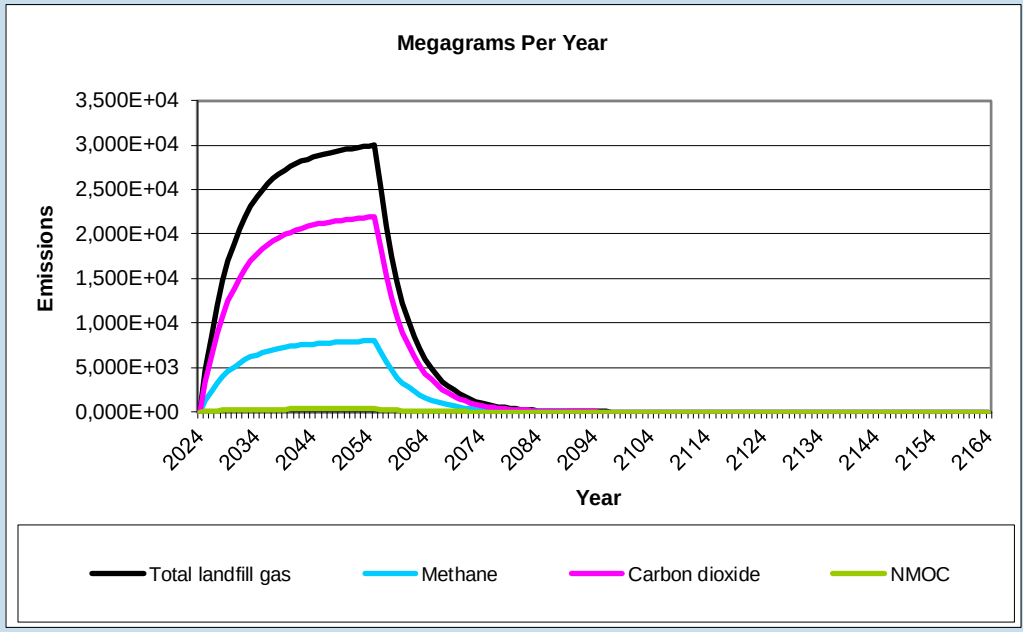

Figure 2. Gas emissions from Landfill modeling at the Jatibarang Landfill for the operating period 2024 to 2054 (in Megagrams/year)

It can be seen that LFG (total Landfill gas, methane gas, carbon dioxide gas and NMOC gas) experiences the highest peak point in 2055. The increase in the amount of methane gas and carbon dioxide will continue to increase along with the increase in the amount of waste entering the landfill (Prilindatami & Cahyonugroho, 2023). In line with the results of research by Prilindatami & Cahyonugroho (2023), this happens because 2054 is considered the final year of landfill operation, so that in 2055 the landfill will no longer accept waste. So that the results of gas emissions in 2054 will accumulate in 2055. In the graph, it can be seen that the peak point of LFG produced for methane gas at the Jatibarang Landfill is 29,961 Mega grams/year or 23,991,671 m3/year. It is estimated that LFG (total landfill gas, methane gas, carbon dioxide gas and NMOC gas) will drop significantly starting in 2056.

The presence of methane gas and carbon dioxide gas in landfills is due to the presence of decomposing bacteria that can decompose organic compounds into simpler compounds. Very high rainfall results in the condition of garbage piles in aerobic conditions (little or no oxygen) so that the growth of microorganisms or bacteria increases. The gas in the landfill that arises is also affected by the type of waste that exists. If the majority of the types of waste in the landfill are organic waste, then the gas produced will be more (Prilindatami & Cahyonugroho, 2023).

The peak of methane gas production a year after the closure of the landfill can be caused by several factors, namely:

1. Organic waste decomposition process: When organic waste is decomposed, anaerobic bacteria produce methane as a byproduct. After the closure of the landfill, the decomposition process is still continuing, and it is possible that there is still a large amount of organic waste that has not fully decomposed inside the landfill. This decomposition process can reach its peak because the organic waste left behind in the landfill has reached optimal conditions for the growth of methanogenic bacteria.
2. Increased temperature: After the closure of the landfill, air access into the landfill is limited, which can lead to an increase in the temperature inside. The increase in temperature accelerates the process of decomposition and production of methane by methanogenic bacteria.
3. Changes in conditions inside the landfill: After the closure of the landfill, there can be changes in the microbiological and physical conditions inside. There may be an increase in humidity, pH, or the availability of nutrients that favor the growth of methanogenic bacteria, resulting in peak methane production (Nurjaya & Rachmanto, 2023).

However, after reaching the peak of production, methane production tends to decline over time. Some of the reasons why methane production declined after its peak include:

1. Decrease in food sources: After some time, the amount of organic waste left in the landfill will be significantly reduced. Lack of sufficient food sources for methanogenic bacteria will result in decreased methane production.

2. Declining environmental conditions: The process of decomposition of organic waste in landfills changes environmental conditions gradually. Changes in pH, humidity, and nutrient availability can be detrimental to the growth of methanogenic bacteria. This can inhibit methane production.
3. Possible methane release: After the closure of a landfill, efforts to control greenhouse gas emissions are usually carried out. Methane gas capture and processing systems can be installed to reduce emissions. Therefore, although there is still methane production in landfills, most of the methane may be captured or channeled to prevent direct release into the atmosphere (Nurjaya & Rachmanto, 2023).

Gas Emissions by Adding Landfill Cells in Landfills

The results of LandGEM modeling have been carried out on 4 Landfill cells with a design distance of each cell every 5 years, namely Landfill with an operational period of 2024 – 2054, an operational period of 2030 – 2060, an operational period of 2035 – 2065 and an operational period of 2040 – 2070. The design of each landfill cell addition is assumed to have the same capacity. Each Landfill cell receives waste input that enters the landfill according to the projected amount of waste generated in the city of Semarang that enters the landfill equally in the same year.

Table 5. Projection of waste entering the Landfill for each cell

Year	Projection of the total waste of Semarang city that enters the landfill	Waste enters the Landfill 2024-2054 (Cell 1)	Waste enters the Landfill 2030-2060 (Cell 2)	Waste enters the Landfill 2035-2065 (Cell 3)	Waste enters Landfill 2040-2070 (Cell 4)
	Tons/year	*Tons/year*	*Tons/year*	*Tons/year*	*Tons/year*
2024	188.305,03	188.700,47	0,00	0,00	0,00
2025	188.700,47	188.700,47	0,00	0,00	0,00
2026	189.096,74	189.096,74	0,00	0,00	0,00
2027	189.493,84	189.493,84	0,00	0,00	0,00
2028	189.891,78	189.891,78	0,00	0,00	0,00
2029	190.290,55	190.290,55	0,00	0,00	0,00
2030	190.690,16	190.690,16	0,00	0,00	0,00
2031	191.090,61	95.545,31	95.545,31	0,00	0,00
2032	191.491,90	95.745,95	95.745,95	0,00	0,00
2033	191.894,03	95.947,02	95.947,02	0,00	0,00
2034	192.297,01	96.148,51	96.148,51	0,00	0,00
2035	192.700,84	96.350,42	96.350,42	0,00	0,00
2036	193.105,51	64.368,50	64.368,50	64.368,50	0,00
2037	193.511,03	64.503,68	64.503,68	64.503,68	0,00
2038	193.917,40	64.639,13	64.639,13	64.639,13	0,00
2039	194.324,63	64.774,88	64.774,88	64.774,88	0,00
2040	194.732,71	64.910,90	64.910,90	64.910,90	0,00
2041	195.141,65	48.785,41	48.785,41	48.785,41	48.785,41
2042	195.551,45	48.887,86	48.887,86	48.887,86	48.887,86
2043	195.962,10	48.990,53	48.990,53	48.990,53	48.990,53
2044	196.373,62	49.093,41	49.093,41	49.093,41	49.093,41
2045	196.786,01	49.196,50	49.196,50	49.196,50	49.196,50
2046	197.199,26	49.299,81	49.299,81	49.299,81	49.299,81
2047	197.613,38	49.403,34	49.403,34	49.403,34	49.403,34
2048	198.028,37	49.507,09	49.507,09	49.507,09	49.507,09
2049	198.444,23	49.611,06	49.611,06	49.611,06	49.611,06
2050	198.860,96	49.715,24	49.715,24	49.715,24	49.715,24
2051	199.278,57	49.819,64	49.819,64	49.819,64	49.819,64
2052	199.697,05	49.924,26	49.924,26	49.924,26	49.924,26
2053	200.116,42	50.029,10	50.029,10	50.029,10	50.029,10
2054	200.536,66	50.134,17	50.134,17	50.134,17	50.134,17
2055	200.957,79	50.239,45	50.239,45	50.239,45	50.239,45
2056	201.379,80	0,00	67.126,60	67.126,60	67.126,60
2057	201.802,70	0,00	67.267,57	67.267,57	67.267,57

2058	202.226,48	0,00	67.408,83	67.408,83	67.408,83
2059	202.651,16	0,00	67.550,39	67.550,39	67.550,39
2060	203.076,72	0,00	67.692,24	67.692,24	67.692,24
2061	203.503,19	0,00	67.834,40	67.834,40	67.834,40
2062	203.930,54	0,00	0,00	101.965,27	101.965,27
2063	204.358,80	0,00	0,00	102.179,40	102.179,40
2064	204.787,95	0,00	0,00	102.393,98	102.393,98
2065	205.218,00	0,00	0,00	102.609,00	102.609,00
2066	205.648,96	0,00	0,00	102.824,48	102.824,48
2067	206.080,83	0,00	0,00	0,00	206.080,83
2068	206.513,60	0,00	0,00	0,00	206.513,60
2069	206.947,27	0,00	0,00	0,00	206.947,27
2070	207.381,86	0,00	0,00	0,00	207.381,86

The cumulative results can be seen in the figure below for the LFG emissions (total landfill gas, methane gas, carbon dioxide gas and NMOC gas) produced against each landfill cell and the total accumulation of the four cells.

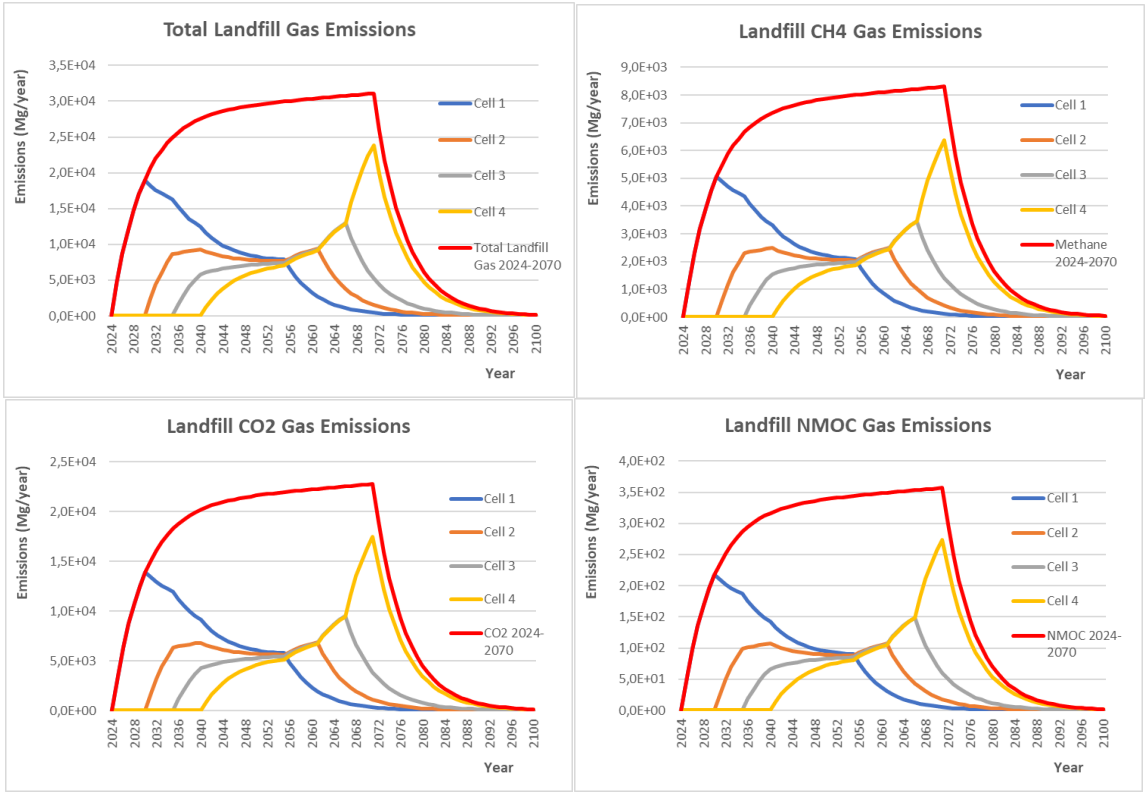

Figure 3. LFG emissions (total landfill gas, methane gas, carbon dioxide gas and NMOC gas) produced against each landfill cell and the total accumulation of the four cells (in Mega grams/year)

Regarding the comparison of methane gas produced from the total accumulation of 4 Landfill cells with 1 Landfill cell to the amount of waste generated into the same landfill, Figure 4 provides an explanation that with 4 Landfill cells, the total methane gas emissions produced will be the same until the year when 1 cell for the 2024-2054 operational period is closed, namely until 2055. For methane gas produced by 1 cell for the 2024-2054 operational period, according to the previous explanation, it will decrease. Meanwhile, methane gas produced from 4 landfill cells after 2055 will continue to increase, although not significantly until 2071. This is because there are still Landfill cells operating after 2054, namely cells 2, 3 and 4 with the amount of waste entering the Landfill not decreasing according to projections. Likewise, when cell 2 is closed in 2060, cells 3 and 4 continue to operate without experiencing a decrease in the amount of waste that enters. This continues until the closure of cell 4, which is in 2070.

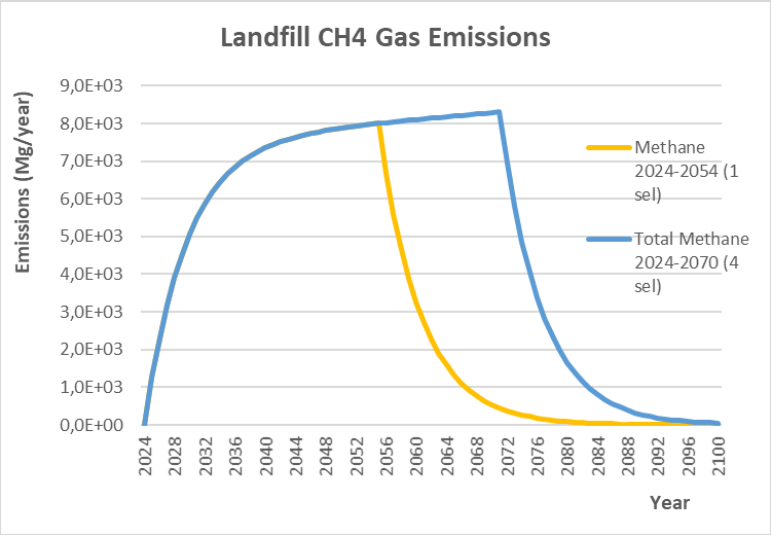

Figure 4. Comparison of methane gas emissions produced against 1 Landfill cell (operating period 2024 – 2054) with 4 Landfill cells (total operating period 2023 – 2070)

Although there is a potential profit for 4 Landfill cells from waste that can continue to be accommodated until cell 4 is closed and the potential for methane gas that can be used as energy, there are several accompanying challenges, namely:

1) Because each cell has the same area capacity, a very large landfill area is needed for a 4-cell landfill design. At least 4 times the landfill area is needed in the landfill.
2) Each cell has a different operation, so more Landfill operators are needed for the stacking and closing process.
3) In addition to requiring area investment, it also requires investment in supporting equipment for each cell. So that the costs needed are also getting higher, including the cost of maintaining equipment infrastructure.
4) The potential for environmental pollution, both air and soil through leachate, will be higher because the area of landfill cells is increasing.

Potential of Electrical Energy Produced

LFG emissions produced from landfills, especially methane gas, have the potential to be further processed, either to produce energy (heat or electricity) or to reduce the Global Warming Potential (GWP) value before being released into the environment. Malav et al. (2020) mentioned that there are several key steps in the collection, processing, and final use of LFG such as: (1) Decomposition of waste in landfills, (2) LFG extraction wells and pipelines, (3) Primary treatment of LFG, (4) Additional treatment for quality improvement and (5) Utilization as a source of renewable energy. Chandra & Ganguly (2023) explained that methane gas left in landfills is one of the largest causes of greenhouse gas emissions. He added, by utilizing methane gas to generate electricity, it will indirectly reduce greenhouse gas emissions.

There are at least three main reasons why landfill gas must be managed with Waste to Energy (WTE) technology Ramprasad et al. (2022). First, landfill gas is the main constituent of greenhouse gases and has the potential to produce energy. Second, methane gas and carbon dioxide gas are always produced through the process of microorganisms in waste generation. Third, methane gas can be extracted and used as a sustainable alternative energy source.

This high amount of methane and carbon dioxide gas content needs special attention. Considering that if this gas is collected in high content, it will have an impact on human health and the surrounding environment. Therefore, it is necessary to process or utilize this hazardous gas. Some landfills in Indonesia have utilized these harmful gases by converting them into electrical energy, or commonly referred to as PLTSA (Final Waste Power Plant) (Prilindatami & Cahyonugroho, 2023).

Waste to Energy (WtE) technology is a technology that can convert waste into new energy or electricity, in other words this technology uses it as the main fuel to produce electrical energy, this technology is commonly referred to as PLTSa (Qodriyatun, 2021). With the implementation of waste management with the PLTSa system, the amount of waste volume can be controlled and can produce renewable energy. One of the widely developed PLTSa technologies is technology that uses landfill gas as fuel to drive generators and generate

electricity, landfill gas is a gas produced from the solid-state fermentation process in the landfill system, the main content of landfill gas producing electrical energy is methane (Yendi & Sabrin, 2021).

Waste Power Plant or often called PLTSa is a type of electrical energy plant that uses waste as the main material. In addition to producing electrical energy, PLTSa plays a role in reducing the amount of waste in the community. So that PLTSa is one of the efforts to overcome environmental pollution that is very useful in the community. The following is the general flow of waste utilization for electrical energy generation:

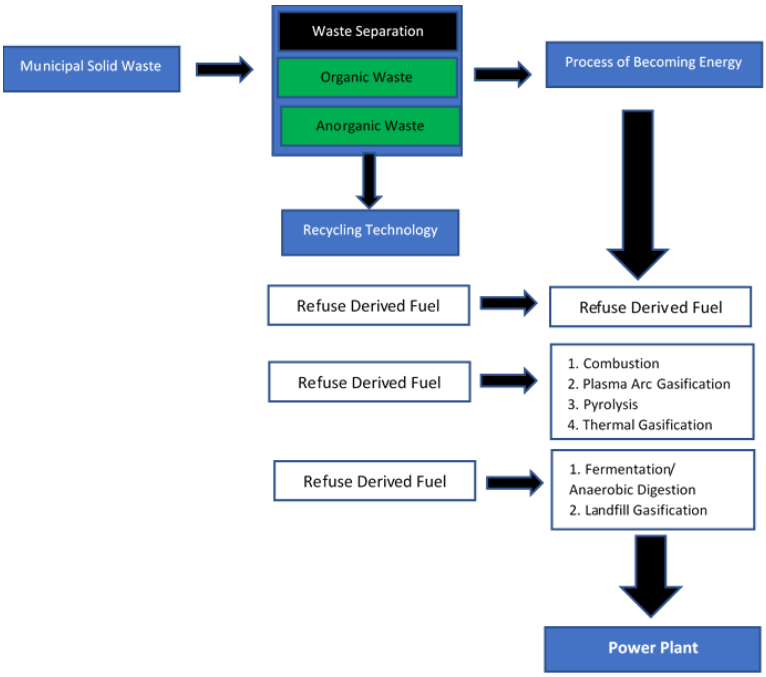

Figure 5. General stages of the PLTSa process
Source: https://tutoriallingkungan.blogspot.co.id

The use of waste in general for the generation of electrical energy is by utilizing methane gas produced from landfill emissions. The conversion of methane gas to the amount of electrical energy produced is calculated by the equation provided by Ayodele et al. (2017) to calculate the potential for electrical energy generation (Ep in kWh/year).

$$\text{Ep} = \frac{QCH_4 \; x \; \lambda CH_4 \; x \; \eta \; x \; LHVCH_4 \; x \; 0.9}{3.6}$$

where QCH4 is the amount of methane produced from the landfill per year, λCH4 is the efficiency of methane collection in the landfill and is taken by 75% (Ayodele et al., 2017), LHVCH4 is the lowest calorific value of CH4 taken at 37.2 MJ/m3, the oxidation factor taken is 0.9 (Ayodele et al., 2017), η is the electricity conversion efficiency for the internal combustion engine provided by 35%. The conversion factor from MJ to kWh is 3.6 Ayodele et al. (2018).

From the above equation, the potential for electrical energy generation (Ep in kWh/year) for CH4 gas emissions produced from the Jatibarang Landfill Landfill per year from the second year period after producing methane gas to the landfill closure period. Meanwhile, another search to calculate the potential electrical power capacity produced by methane gas can be calculated using the following equation:

Total electricity = Methane gas x 11.17 kWh

The heat potential of 1 kg of methane gas is equivalent to 6.13 x 107J, and 1 kWh of electricity is equivalent to 3.6 x 106J, so 1 m3 of methane gas is equivalent to 11.17 kWh (Kusuma et al., 2020). In this case, the calculation of the potential for electrical energy generation (Ep in kWh/year) was used according to the equation used by Ayodele et al. (2017). The table and figure below are the results of the calculation of the potential for electrical energy generated from methane gas projections, both for 1 Landfill cell for the operational period 2024 – 2054 and the accumulation of 4 Landfill cells with a total duration of the operational period 2024 – 2070.

Table 6. Potential for electrical energy generation (Ep) for 1 cell and 4 Landfill cells

Year	Methane4 gas emissions from landfill cells for the period 2024-2070 (m3/year)	Methane1 gas emissions from landfill cells for the period 2024-2054 (m3/year)	Potential for electrical energy generation (Ep) in kWh/year	
			4 Landfill cells for the 2024-2070 period	*1 Landfill cell for the 2024-2054 period*
2024	0	0	0	0
2025	1.881.911	1.881.911	4.594.216	4.594.216
2026	3.457.768	3.457.768	8.441.276	8.441.276
2027	4.777.994	4.777.994	11.664.278	11.664.278
2028	5.884.708	5.884.708	14.366.044	14.366.044
2029	6.813.091	6.813.091	16.632.458	16.632.458
2030	7.592.526	7.592.526	18.535.255	18.535.255
2031	8.247.559	8.247.559	20.134.354	20.134.354
2032	8.798.691	8.798.691	21.479.804	21.479.804
2033	9.263.045	9.263.045	22.613.409	22.613.409
2034	9.654.925	9.654.925	23.570.087	23.570.087
2035	9.986.279	9.986.279	24.379.003	24.379.003
2036	10.267.084	10.267.084	25.064.519	25.064.519
2037	10.505.676	10.505.676	25.646.983	25.646.983
2038	10.709.018	10.709.018	26.143.391	26.143.391
2039	10.882.925	10.882.925	26.567.941	26.567.941
2040	11.032.254	11.032.254	26.932.490	26.932.490
2041	11.161.063	11.161.063	27.246.944	27.246.944
2042	11.272.739	11.272.739	27.519.575	27.519.575
2043	11.370.115	11.370.115	27.757.293	27.757.293
2044	11.455.554	11.455.554	27.965.872	27.965.872
2045	11.531.032	11.531.032	28.150.131	28.150.131
2046	11.598.197	11.598.197	28.314.099	28.314.099
2047	11.658.428	11.658.428	28.461.138	28.461.138
2048	11.712.876	11.712.876	28.594.060	28.594.060
2049	11.762.503	11.762.503	28.715.210	28.715.210
2050	11.808.110	11.808.110	28.826.549	28.826.549
2051	11.850.369	11.850.369	28.929.714	28.929.714
2052	11.889.841	11.889.841	29.026.074	29.026.074
2053	11.926.993	11.926.993	29.116.771	29.116.771
2054	11.962.215	11.962.215	29.202.758	29.202.758
2055	11.995.836	11.995.836	29.284.834	29.284.834
2056	12.028.127	10.019.764	29.363.664	24.460.750
2057	12.059.316	8.369.211	29.439.805	20.431.336
2058	12.089.594	6.990.552	29.513.721	17.065.686
2059	12.119.119	5.839.000	29.585.800	14.254.459
2060	12.148.025	4.877.143	29.656.366	11.906.325
2061	12.176.422	4.073.732	29.725.691	9.944.999
2062	12.204.404	3.402.667	29.794.001	8.306.761
2063	12.232.047	2.842.147	29.861.485	6.938.390
2064	12.259.416	2.373.960	29.928.300	5.795.431
2065	12.286.566	1.982.898	29.994.580	4.840.751
2066	12.313.542	1.656.256	30.060.433	4.043.335
2067	12.340.380	1.383.421	30.125.953	3.377.277
2068	12.367.114	1.155.531	30.191.217	2.820.939
2069	12.393.769	965.180	30.256.288	2.356.246
2070	12.420.367	806.186	30.321.220	1.968.102
2071	12.446.927	673.383	30.386.060	1.643.897
2072	10.396.547	562.457	25.380.571	1.373.098
2073	8.683.926	469.804	21.199.635	1.146.908

2074	7.253.425	392.413	17.707.423	957.978
2075	6.058.570	327.771	14.790.483	800.171
2076	5.060.543	273.777	12.354.050	668.359
2077	4.226.921	228.678	10.318.970	558.260
2078	3.530.621	191.008	8.619.128	466.298
2079	2.949.022	159.543	7.199.301	389.485
2080	2.463.231	133.262	6.013.362	325.325
2081	2.057.463	111.310	5.022.782	271.734
2082	1.718.538	92.974	4.195.380	226.972
2083	1.435.443	77.658	3.504.276	189.583
2084	1.198.983	64.865	2.927.017	158.353
2085	1.001.475	54.180	2.444.850	132.267
2086	836.502	45.255	2.042.111	110.479
2087	698.705	37.800	1.705.714	92.280
2088	583.608	31.573	1.424.732	77.079
2089	487.470	26.372	1.190.036	64.381
2090	407.169	22.028	994.002	53.776
2091	340.096	18.399	830.260	44.917
2092	284.072	15.368	693.492	37.518
2093	237.277	12.837	579.253	31.338
2094	198.191	10.722	483.833	26.176
2095	165.543	8.956	404.131	21.864
2096	138.273	7.481	337.559	18.262
2097	115.495	6.248	281.953	15.254
2098	96.470	5.219	235.507	12.741
2099	80.578	4.359	196.712	10.642
2100	67.305	3.641	164.307	8.889

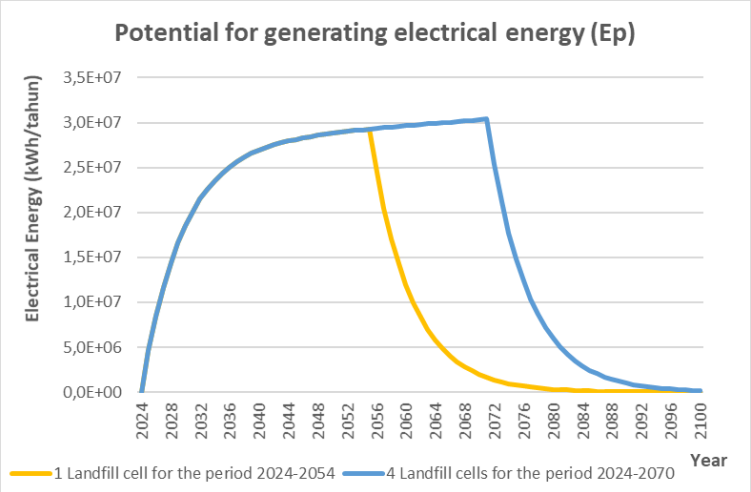

Figure 6. Potential for electrical energy generation (Ep) for 1 cell and 4 Landfill cells (in kWh/year)

Based on the results of the calculation of the electricity generation potential above, it can be seen that for a landfill with 1 cell has the same electrical energy potential as 4 cells until 2055, 1 year after the closure of the 1-cell landfill (in 2054), and is the peak of electrical energy that has the potential to be generated. The value of the potential electrical energy produced at this peak is 29,284,834 kwh/year or 29,284.8 Mwh/year. Where this is in line with the projected methane gas emissions produced. The amount of energy present in biogas depends on the concentration of methane (Subekti et al., 2023). The higher the methane content, the greater the energy content (caloric value) of biogas, on the other hand, the smaller the methane content, the smaller the caloric value.

Meanwhile, for Landfill with 4 cells, it will continue to rise, until 2071, 1 year after the closure of the 4-cell Landfill (in 2070). The value of the potential electrical energy produced at the top of the 4-cell landfill is 30,386,060 kwh/year or 30,386.1 Mwh/year. Although for the 4-cell landfill, the increase is not significant,

but as long as it is still operating from 2055 to 2071, it provides the potential for electrical energy that can continue to be utilized.

Discussion and Recommendation

Flue gases produced from a landfill have been discussed in Chapter II. In table 6, the largest majority of gas content found in LFG is methane of 45 – 60 % and carbon dioxide content of 25 – 50 %. Both methane and carbon dioxide gases have a role in increasing the warming of the earth's temperature and are categorized as greenhouse gases (GHGs). Landfill gas produced at landfills will be dangerous if not managed and controlled properly. The methane gas content in LFG is a flammable gas so that the risk of explosion around the landfill location is very high (Soleh et al., 2020). Landfill Gas or LFG is a gas produced by microbes when organic matter undergoes a fermentation process in an anaerobic state that is suitable in terms of temperature, humidity, and acidity.

Methane gas (CH4) is more concerned because it is a greenhouse gas and also has a Global Warming Potential (GWP) 21 times stronger than carbon dioxide (CO2) (Marten & Newbold, 2012). Carbon dioxide emitted from solid waste management is biologically not included in the greenhouse gas inventory of a landfill, because carbon dioxide is categorized as biogenic origin and calculated as net emission. Other gases produced are also not counted because they are not significant in size. The recommendations of this report focus on the management of methane biogas produced from landfills. As previously discussed, the potential for electrical energy that can be generated has been discussed. So the recommendation that will be discussed is the management of methane biogas emissions by being used as electrical energy.

Some of the gas processing in the landfill includes flaring, purification to become biogas, and conversion into electricity. Flaring is used to burn methane and carbon dioxide gases so that they become gases that are not harmful to the environment. The enclosed flare system requires a temperature of 1000°C and must be maintained for a long period of time (Damanhuri & Padmi, 2010). Flaring technology has advantages in operating and maintenance criteria. Flaring is easy to operate because there is no need for pretreatment for methane gas to be burned. Maintenance is easy because there are not too many components that must be maintained. Flaring only has to maintain the air supply used so that it can be completely combustioned so that it can meet the existing emission standards in accordance with regulations. However, considering the large potential for converting methane gas emissions into electrical energy, it is still recommended to process methane gas emissions into electrical energy.

The biogas purification method, in this case biogas, uses the method of absorbing carbon dioxide with water. This technology is designed to absorb carbon dioxide in 40% of the biogas content so that the percentage of methane gas increases from 60% to >95% (Uusitalo et al., 2013). The purified clear gas is called biogas. The biogas gas is then compressed into the CNG cylinder to be utilized as fuel. The amount of energy for biogas purification processing and compression is 25% of the total biogas energy produced per day. The technology to convert methane gas into biogas requires a lot of pretreatment, including water scrubbing, membrane separation, molecular sieve and if it is flowed using pipes to the community for use, a proper and good pipeline is needed (EPA, 2017). Methane gas conversion technology has advantages because it has a higher utilization potential compared to biogas. The concentration of methane gas needed to convert into electricity using this technology is a minimum of 45%. Maintenance and operation are easy because it only requires pretreatment dewatering.

Methane gas to electricity conversion technology is easy to apply and has been used as a technology to maximize the potential of methane gas into electricity. 70% of landfills in the United States have converted methane gas into electricity with a conversion capacity of 1 million tons in landfills can be converted into 0.8 MegaWatts of electricity (EPA, 2015).

Gas from landfills can be used directly or for power generation. Direct use in the way of producing steam or hot water for the production process of goods, fuel for heating furnaces and dryers, heating rooms, and evaporating leachate from landfills which is useful so that the cost of processing leachate becomes cheaper. Gas power plants from landfills can be used to power combustion engines and gas turbines that generate electricity again (Global Metan Initiative, 2012).

The existence of Waste Power Plants (PLTSa) at the Waste Disposal Site (TPA) is considered as part of the government's program in order to realize the Clean Indonesia Movement. The Clean Indonesia Movement Program is one of the Mental Revolution Movements listed in Presidential Instruction Number 12 of 2016. The construction of PLTSa is based on Presidential Decree Number 35 of 2018 concerning the Acceleration of the Construction of Waste Processing Plants into Electrical Energy Based on Environmentally Friendly Technology. Sorting organic and inorganic waste so that it does not inhibit the anaerobic decomposition process. An innovation that can be applied is the construction of a Waste Power Plant (PLTSa) by utilizing organic waste as an effort to reduce carbon emissions in the environment. There is a study on waste processing innovation into electrical energy (PSEL) as an alternative to waste management (Subekti et al., 2023).

The stages of the energy flow process in the waste-to-energy power generation system are derived from energy sourced from biomass (Subekti et al., 2023). Biomass is then converted into energy in the form of gas through an anaerobic process in the landfill system. After passing through the filter, the calorific value per m3 of gas increases. This is due to the reduction of CO2 gas by 20% per m3 of biogas that enters the filter system. After going through the preheating process with a heat exchanger, the purified biogas is then used as fuel for the generator of the homogeneous charge compression ignition engine (HCCI). HCCI engine generators have an efficiency of more than 40%. Approximately 60% of the lost energy is included in the exhaust gas which is then used as a heat source in the heat exchanger system for biogas pre-hating.

The process of converting methane gas into electricity begins from a collection well to separate water and methane gas with an application system. Then it is flowed to the internal combustion system station. Engines that receive methane gas are burned with the help of oxidants in their combustion vessels. Inside this machine, the high-temperature expansion and high-pressure gas produced apply the force to the engine. This force will drive the piston, turbine blade, or nozzle.

In electricity generation, an electric generator will be used, where the maintenance of the generator is not only the maintenance of the instruments and equipment, but also the quality of the incoming biogas (methane gas) input. The quality of biogas can be improved by removing hydrogen sulfur, water content, and carbon dioxide (Subekti et al., 2023). The reason is, hydrogen sulfur contains toxins and substances that cause corrosion. If biogas contains these compounds, then the gas generated becomes harmful. Meanwhile, the water content in biogas can reduce the activity of biogas and can cause corrosiveness. The content of hydrogen sulphur, water and carbon dioxide can be removed by using desulfurizing tools or materials, which are needed to power the generator without being exposed to corrosion. Gas from landfills needs to be cleaned before being used as a renewable energy source. Cleaning is needed to reduce moisture content and remove contaminants contained in gases in order to prevent correlation from tools and systems (Rajaram et al., 2012).

The gas taken from pipes in the landfill contains various gases, including methane, carbon dioxide, nitrogen, sulfur, and other gases. The gas taken must be purified first in order to be able to get a good level of purity so that it can be used as electricity. Nitrogen, sulfur, and siloxen gases must be removed by the main treatment method. The main processing used is adsorption and absorption. Adsorption removes siloxen by using silica which will later remove the concentration of siloxen in the gas. Absorption removes sulfur by reacting sulfur with chemicals. The concentration of carbon dioxide was reduced by using the water scrubbing method. Water scrubbing uses water to dilute the gas that enters the system so that the carbon dioxide reduction process occurs. The gas from the landfill is fed into the reactor which is then sprayed with pressurized water and carbon dioxide, nitrogen, and oxygen will dissolve along with the water while methane gas that has a smaller dilution capability value will pass through it and become pure methane gas with a purity level of 96-99%. The excluded gas will be collected and burned using the flaring method (Global Metan Initiative, 2012).

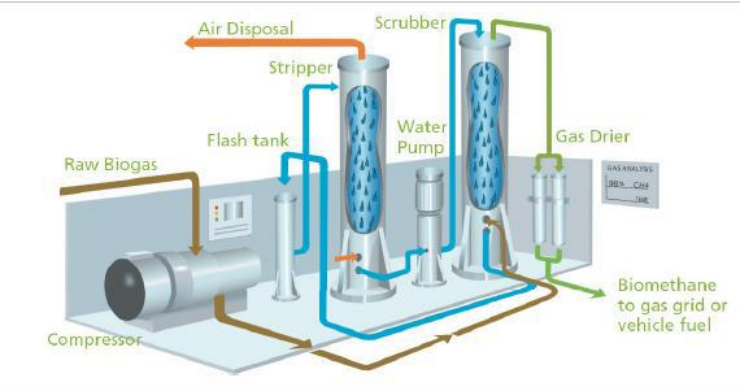

Figure 7. Water Scrubbing Technology
Source: EPA, 2015

Methane gas technology that is converted into electricity uses an Internal Combustion Engine. The working principle of the Internal Combustion Engine is by igniting gas from the landfill with air in the combustion chamber. This technology is easy to build and can work for up to 20 years of use if properly maintained. This technology has a high noise level of 80 – 110 db so technology is needed to reduce noise (Tsatsarelis et al., 2006). The machine can improve its work efficiency if heat recovery from the landfill can be carried out. The recovery system used is Combine Heat and Power (CHP). Combined heat and power (CHP) or often called a cogeneration system is a series or generation of several forms of useful energy (usually

mechanical and thermal) simultaneously in one integrated system. The CHP system consists of a number of individual components of the prime mover, generator, heat recovery, and electrical connections combined into an integration (Haq, 2012).



Figure 8. Internal Combustion Engine Technology
Source: EPA, 2015

Based on the discussion, the landfill with 1 cell produces methane gas emissions at its peak in 2055 of 19,665,305 m3/year and has the potential for electrical energy up to its highest peak in 2055, worth 48,007,925 kwh/year or 48 Gwh/year. For Landfill with 1 cell of electrical energy potential in the first year (2024) there is still no electricity because methane gas emissions have not been produced, then in the second year after operation the value of electrical energy potential in 2025 is 7.5 Gwh/year. Meanwhile, the landfill with 4 cells produces methane gas emissions at its peak in 2055 of 20,404,798 m3/year and the potential value of electrical energy produced at its peak in 2071 is 49.8 Gwh/year or 49,813.2 Mwh/year.

As a comparison, the results of research conducted by (Haq, 2012) on studies related to the potential of waste-to-energy plants in Banjarmasin City. Researchers calculated the potential of methane gas from the Basirih Landfill in Banjarmasin and then processed and converted into electricity for their own use and had excess electricity which was then sold to PT. PLN Persero. The Basirih Landfill has a methane gas potential of 8,176,975 m3/year. The electrical energy produced by the plant is 12,848,929 kWh while the electrical energy used for its own use is 866,162 kWh so that the electrical energy that can be sold to PT. PLN (Persero) of 11,956,766 kWh. The technology used in the study is Internal Combustion Engine technology which is equipped with heat recovery facilities to improve the efficiency of electricity production.

It can be concluded that from the results of modeling methane gas emissions from the landfill at the Jatibarang Landfill, Semarang city, which has been calculated, the potential for electrical energy that can be generated is high enough to be recommended for management using the concept of Waste to Energy (WTE) into electrical energy. The technology of converting methane gas into electricity using an internal combustion engine has a gas processing range of 0.8 – 3 MW for each engine (Naranayan & Shresta, 2007). Methane gas production below 0.8 MW is not appropriate to convert because it is too little to cause losses.

Meanwhile, for the design of a Landfill with 4 cells, although there is a potential profit for 4 Landfill cells from waste that can continue to be accommodated until cell 4 is closed and the potential of methane gas that can be used as energy, there are several challenges that accompany it so that it is necessary to consider the sustainability of various aspects of the potential value of the energy produced.

CONCLUSION

The increase in population and economic growth in urban areas leads to a significant rise in waste volume, necessitating effective waste management solutions such as the Waste Power Plant (PLTSa) at the Jatibarang Landfill, which accommodates 70% of Semarang City's waste. The landfill processes approximately

800-900 tons of waste daily, with 62% being organic waste, primarily food waste, which produces methane gas during anaerobic decomposition. Modeling using the LandGEM software forecasts that methane gas emissions will peak in 2055, with the potential for energy generation reaching 29 GWh/year from a single landfill cell, and up to 30.4 GWh/year from multiple cells by 2071. While converting landfill gas to electricity presents significant benefits for energy supply and reducing greenhouse gas emissions, challenges remain regarding sustainability and effective management practices. Future research should focus on the feasibility of implementing PLTSa, evaluate different landfill designs, and consider community engagement and policy frameworks to support waste-to-energy initiatives.

REFERENCES

Aghdam, E. F., Scheutz, C., & Kjeldsen, P. (2019). Impact of meteorological parameters on extracted landfill gas composition and flow. *Waste Management*, *87*. https://doi.org/10.1016/j.wasman.2018.01.045

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Alao, M. A. (2017). Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria. *Applied Energy*, *201*. https://doi.org/10.1016/j.apenergy.2017.05.097

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Alao, M. A. (2018). Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria. *Journal of Cleaner Production*, *203*. https://doi.org/10.1016/j.jclepro.2018.08.282

Chandra, S., & Ganguly, R. (2023). Assessment of landfill gases by LandGEM and energy recovery potential from municipal solid waste of Kanpur city, India. *Heliyon*, *9*(4). https://doi.org/10.1016/j.heliyon.2023.e15187

Damanhuri, E., & Padmi, T. (2010). *Pengelolaan Sampah*. Program Studi Teknik Lingkungan FTSL ITB.

EPA. (2015). *Landfill Methane Utilization*.

EPA. (2017). *LFG Energy Project Development Handbook*. U.S. Environmental Protection Agency.

Fallahizadeh, S., Rahmatinia, M., Mohammadi, Z., Vaezzadeh, M., Tajamiri, A., & Soleimani, H. (2019). Estimation of methane gas by LandGEM model from Yasuj municipal solid waste landfill, Iran. *MethodsX*, *6*. https://doi.org/10.1016/j.mex.2019.02.013

Global Metan Initiative. (2012). International Best Practices Guide for LFGE Project. *Landfill Gas Energy Utilization Technologies*.

Hapsari, F., & Wahyuni, S. (2020). Making An Ecobrick as An Effort to Grow An Eco-Friendly School in SMP PGRI 30 Jakarta in Order to Support the Adiwiyata School Program. *Literatus-Neolectura Publication Jurnals*, *2*(2).

Haq, A. N. (2012). *Studi Potensi Pembangkit Listrik Tenaga Sampah di Kota Banjarmasin* [Doctoral Dissertation]. Universitas Diponegoro.

Harjanti, I. M., & Anggraini, P. (2020). Pengelolaan Sampah Di Tempat Pembuangan Akhir (TPA) Jatibarang, Kota Semarang. *Jurnal Planologi*, *17*(2). https://doi.org/10.30659/jpsa.v17i2.9943

Kementerian Lingkungan Hidup dan Kehutanan. (2020). *Sistem Informasi Pengelolaan Sampah Nasional (SIPSN)*. Kementerian Lingkungan Hidup Dan Kehutanan.

Kusuma, V. A., Hasanah, B., & Slamet, S. (2020). Forecasting Potensi Energi Gas Metana menggunakan Pembangkit Listrik Tenaga Sampah (PLTSa) pada TPA Manggar kota Balikpapan. *JEECAE (Journal of Electrical, Electronics, Control, and Automotive Engineering)*, *5*(2). https://doi.org/10.32486/jeecae.v5i2.533

Malav, L. C., Yadav, K. K., Gupta, N., Kumar, S., Sharma, G. K., Krishnan, S., Rezania, S., Kamyab, H., Pham, Q. B., Yadav, S., Bhattacharyya, S., Yadav, V. K., & Bach, Q. V. (2020). A review on municipal solid waste as a renewable source for waste-to-energy project in India: Current practices, challenges, and future opportunities. *Journal of Cleaner Production*, *277*. https://doi.org/10.1016/j.jclepro.2020.123227

Marten, A. L., & Newbold, S. C. (2012). Estimating the social cost of non-CO2 GHG emissions: Methane and nitrous oxide. *Energy Policy*, *51*, 957–972. https://doi.org/10.1016/j.enpol.2012.09.073

Naranayan, G., & Shresta, S. O. B. (2007). *Landfill Gas – A Fuel for Internal Combustion Engine Applications*. Western Michigan University.

Nurjaya, L. A. N. W., & Rachmanto, T. A. (2023). Potensi Produksi Gas Metana (CH4) dari Kegiatan Landfilling di TPA Bengkala Kabupaten Buleleng dengan Kombinasi Permodelan LandGEM, IPCC, dan LCA. *JURNAL ENVIROTEK*, *15*(2). https://doi.org/10.33005/envirotek.v15i2.262

Prilindatami, R., & Cahyonugroho, O. H. (2023). Estimasi Emisi Gas Rumah Kaca (GRK) di TPA Benowo Menggunakan Model LandGem. *JURNAL SAINS TEKNOLOGI & LINGKUNGAN*, *9*(4). https://doi.org/10.29303/jstl.v9i4.518

Qodriyatun, S. N. (2021). Pembangkit Listrik Tenaga Sampah: Antara Permasalahan Lingkungan dan Percepatan Pembangunan Energi Terbarukan. *Aspirasi: Jurnal Masalah-Masalah Sosial*, *12*(1). https://doi.org/10.46807/aspirasi.v12i1.2093

Rajaram, V., Siddiqui, F. Z., & Khan, M. E. (2012). *From Landfill Gas to Energy Technologies and Challenges*. CRC Press.

Ramprasad, C., Teja, H. C., Gowtham, V., & Vikas, V. (2022). Quantification of landfill gas emissions and energy production potential in Tirupati Municipal solid waste disposal site by LandGEM mathematical model. *MethodsX*, *9*. https://doi.org/10.1016/j.mex.2022.101869

Soleh, M., Hadiyanto, H., Windarta, J., Anne, O., Hendroko Setyobudi, R., & Mel, M. (2020). Technical and Economic Analysis of Municipal Solid Waste Potential for Waste to Energy Plant (Case Study: Jatibarang Landfill Semarang, Central Java, Indonesia). *E3S Web of Conferences*, *190*. https://doi.org/10.1051/e3sconf/202019000027

Subekti, S., Sasmito, A., & Rahman, B. (2023). PEMANFAATAN SAMPAH DI TEMPAT PEMROSESAN AKHIR (TPA) JATIBARANG SEBAGAI SUMBER ENERGI BARU TERBARUKAN. *Merdeka Indonesia Jurnal International*, *3*(1).

Tsatsarelis, T., Karagiannidis, A., & Perkoulidis, G. (2006). Technologies of landfill gas management and utilization. In *Protection and Restoration of the Environment VIII, Chania*. Aristotle University.

U.S. Environmental Protection Agency. (2020). *Landfill Gas Emissions Model (LandGEM): Estimates emission rates from municipal solid waste landfills*. U.S. Environmental Protection Agency.

Uusitalo, V., Soukka, R., Horttanainen, M., Niskanen, A., & Havukainen, J. (2013). Economics and greenhouse gas balance of biogas use systems in the Finnish transportation sector. *Renewable Energy*, *51*. https://doi.org/10.1016/j.renene.2012.09.002

Yendi, E., & Sabrin, I. G. (2021). Analisis Pembangkit Listrik Tenaga Sampah Dengan Metode Sanitary Landfill di Bantargebang. *Jurnal Sains & Teknologi Fakultas Teknik*, *11*(2), 70–80.

Zaman, B., & Priyambada, I. B. (2007). Pengomposan dengan Menggunakan Lumpur dari Instalasi Pengolahan Air Limbah Industri Kertas dan Sampah Domestik Organik. *Teknik*, *28*(2), 158–166.