Analysis of Electricity Generation from Landfill Gas (Case Study: Manggar Landfill, Balikpapan)

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Abstract. Despite of adverse impacts on the environment, landfill has big potency as renewable energy sources since it generates biogas from organic waste degradation process which can be used for power plant purposes. In 2017, the volume of waste disposed to Manggar Landfill was 128,000 tons, which mostly are organic waste (59.4%). Therefore, this study aims to estimate the amount of energy that can be generated from landfill as methane, by calculating biogas production in landfill based on waste generation, as well as composition using LandGem and Afvalzorg model. In 2017, Manggar landfill produced about $4 \times 10^3$ Mg CH₄/year or about 5.31 to 6.44 × $10^6$ m³/year. The estimated methane then converted to electricity using gas engine and trigeneration methods. Using gas engine, methane from Manggar Landfill is predicted to produce electricity about 787 MWh/month. On the other hand, if trigeneration method applied (by keeping the same gas engine as before), it produces 41.8% of heat which convert to 29.3 kWh of cold. In conclusion, it will be beneficial if Manggar Landfill capture and treat methane for generating electricity since Manggar Landfill produces about $6.44 \times 10^6$ m³/year which can be used for electricity purposes of around 10,000 people using gas engine.

1. Introduction

Landfilling is the most preferable method applied in developing countries, particularly in Indonesia, in handling its municipal solid waste. It is considered as cheap and convenient method since it is not restricted to advanced technology for treating and managing waste. Despite of its economics advantages, landfilling gives many adverse impacts on environment. The failure of landfilling methods may lead to many environmental contaminants due to leachate and which are soil pollution, ground water contamination and air pollution due to emission of greenhouse gases [1]. Therefore, waste management hierarchy put landfilling method as last option preferable due to its adverse effect to environment.

In Balikpapan, landfilling has been practiced many years ago, but proper landfilling area named Manggar landfill was opened in 2002. When opened in 2002, the volume of waste disposed to Manggar landfill was 69,000 tons and in 2017 it reached 128,000 tons. In a period of 15 years, the volume of waste has doubled. Urban waste that is directly piled up still contains a lot of organic waste at 59.4%. Followed by plastic waste, paper, and others, which have a composition respectively: 13.51%, 12.26%, and 10.62%. This high percentage of organic waste gives adverse impact from landfill gas produced by
The advantage of a multi-phase model is that the typical waste composition can be taken into account.
In the Afvalzorg multiphase model, eight waste categories and three fractions are distinguished [14]. For each fraction LFG production is calculated separately. The multi-phase model is a first-order model and can be described mathematically by

$$\alpha_t = \zeta \sum_{i=1}^{3} cA_{i,0}k_{i,1}e^{-k_{i,1}t}$$

where

- $\alpha_t$ = landfill gas production at a given time ($m^3$LFG/y)
- $\zeta$ = dissimilation factor (-)
- $i$ = waste fraction with degradation rate $k_{i,1}$ (kg/kg waste)
- $c$ = conversion factor ($m^3$LFG/kgOM degraded)
- $A$ = amount of waste in place (Mg)
- $C_o$ = amount of organic matter in waste (kgOM/Mg waste)
- $k_{i,1}$ = degradation rate constant of fraction $i$ ($y^{-1}$)
- $t$ = time elapsed since depositing ($y$)

Numerous kinds of machines are available to convert biogas into electricity, which two of these are gas engines and trigeneration, which considered suitable to be applied in Manggar Landfill. Gas engines is thermodynamic machines which transform heat into work. The combustion of the gas mixture is done inside the engine itself, operating a piston in different phases: compression, combustion, expansion, admission, exhaust. Four-stroke spark-ignition biogas engines were originally developed for natural gas. Then, they were adapted to the special features of biogas. Their capacity normally ranges between 100 kW and 1 MW while the electrical efficiency is in the range 34 – 40% [12].

Trigeneration or combined cooling, heat and power system (CCHP) is one step ahead of cogeneration since it aims the simultaneous generation of electricity, useful heating and cooling from a single fuel source [16]. Trigeneration is the extension of cogeneration with the production of cold as additional energy. This resource is produced by a refrigerating machine either by using a part of the electricity generated by the turbine or directly by recovering the heat during the combustion of the biogas in the engine. Thus, an absorption refrigeration machine is indeed capable of producing refrigerated water (of a temperature below 7°C) from an exchanger, such as a pump inverted heat. If cogeneration is not necessary for a country like Indonesia, trigeneration is important because in Balikpapan, air conditioning is one of the first sources of electricity consumption.

### 3. Results and discussion

#### 3.1. Estimation of landfill gas production

Gas emissions from municipal landfills around the world are causing global environmental impacts [7]. Methane is one of the major ingredients of greenhouse gases (GHG) which is responsible for global warming [1]. During the landfilling of waste, organic fractions are degraded which later generates landfill gases (LFGs), consisting mainly of methane (CH$_4$) and carbon dioxide (CO$_2$), which are the main GHG constituents [17]. Waste decomposition does not begin immediately after the disposal but typically with a time delay [18]. Simulations of LFG generation were based on the assumptions that the decomposition of degradable carbon remaining in the landfill follows first-order decay characteristics, and the simulation parameters are adjusted using measured data.

| Year       | Waste Generation (Tonne/year) |
|------------|-------------------------------|
| 2002       | 69,630.20                     |
| Area (Ha) | 2003 | 2004 | 2005 |
|-----------|------|------|------|
| 7.7       | 75,986.21 | 128,855.26 | 77,224.93 |
| 10        | 128,945.49 | 128,945.49 |

| Composition | 2017 | 2017 |
|-------------|------|------|
| %           | ton  | %    | ton  |
| Organics    | 59.4 | 76,585.96 | 2008  | 114,569.19 |
| Can         | 0.81 | 1,044.35  | 2009  | 114,267.40 |
| Aluminium   | 0.09 | 116.04    | 2010  | 112,986.80 |
| Glass       | 1.19 | 1,534.30  | 2011  | 105,661.13 |
| Plastics    | 13.51| 17,418.79 | 2012  | 115,266.12 |
| Paper       | 12.26| 15,807.14 | 2013  | 123,664.87 |
| Metal       | 0.16 | 206.29    | 2014  | 132,994.07 |
| Textile     | 1.97 | 2,539.97  | 2015  | 135,252.47 |
| Others      | 10.62| 13,692.64 | 2016  | 130,671.63 |
| Total       | 128,945.49 | 128,945.49 |

Waste decomposition does not begin immediately after the disposal but typically with a time delay [18]. Therefore, landfill gas will be generated up to several years ahead. Since landfilling had been practiced in decades, it will continue to generate biogas. Estimation of methane production can be approached by theoretical analytical modelling related to the history of the site. This method consists in calculating gas production year by year, based on information received on the quantities and the nature of the waste stored.

As previous research [14], calculation of methane generation by Afvalzorg model is less than calculation by LandGEM model since in Afvalzorg model, waste composition is more detail which have its degradation rate. LFG estimation according to the Multi-phase (Afvalzorg) model is minimum than other models. According to first order model, the entire amount of waste has been taken into consideration for calculation while only slow, medium and fast degradable portions of wastes are considered in Multi-phase model excluding the non-biodegradable or inert materials [1].

![Figure 1. Biogas emissions in Manggar landfill according to LandGEM model (m³/year).](image-url)
Methane is not produced directly after disposed to landfill, it accumulates gas production from the first year which in Manggar Landfill was started on 2002 to estimated landfill age on 2050. The results LandGEM and Afvalzorg model values seem coherent with each other. Based on the calculation, methane production peaked in 2050 about $1.2 \times 10^7$ m$^3$/year in LandGEM model and $8 \times 10^6$ m$^3$/year in Afvazor, then decrease simultaneous before ultimately stop in 2100. In 2017, Manggar landfill produced about $6.44 \times 10^7$ and $5.31 \times 10^6$ m$^3$/year. The methane generation curves of LandGEM and Afvalzorg models are similar and seem to have the same slope as the square root function. The growth of these curves is quite logical considering the increasing waste rate in Manggar (and the quantity is supposed to increase by 2% per year after 2017). And the similarity with the square root function is explained by the diversity of wastes, the organics waste will indeed degrade quickly giving the curve a steep first slope, then the waste such as wood and cloth will take over for finally let the plastics degrade slowly and producing little methane.

3.2. Conversion of methane gas to electricity

The main role of Manggar landfill is not to produce biogas but to store municipal solid waste of Balikpapan City. Therefore, the method applied to capture landfill gas is not effective and profitable. Landfill gas is planned to be captured vertical tubes, which unfortunately were broken by trucks during unloading of waste and no longer operational. Hence, landfill gas was collected by simple plastic pipe that connects a leachate tank to the engine room, consist only a fixed van whose engine shaft operates a 9kW alternator. The gas from the landfill enters directly into the engine (without prior treatment) of the van which, once started, lights up about 1 km of streetlights leading to the landfill.

A second pipe distribute biogas for about a hundred families in biogas. However, many inhabitants had trouble cooking with this untreated gas and also that it was periodic in operating the alternator to produce electricity. Considering that each of this hundreds of families consume 365kWh of this biogas per year (for 4 people) and that the alternator operates for 2 hours a day, the annual energy production due to the biogas from the Manggar landfill is therefore 25 MWh maximum.

Based on the calculation of monthly methane flows in 2017, it will be suitable to pre-size the engine power to 1.1MWe. The goal was not to oversize in order not to degrade the electrical yield or to undersize, because the reference year is 2017, the amount of methane generated by the plant will increase.
as seen previously. Specially designed for biogas engines are offered by various companies and this calculation of electricity production from biogas was using a gas engine of 1200 kWe.

### Table 2. Results of the production of electricity by a gas engine in Manggar

| Unit                  | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sept | Oct  | Nov  | Dec  | Average |
|-----------------------|------|------|------|------|------|------|------|------|------|------|------|------|---------|
| Methane flow          | m³/h | 318  | 261  | 284  | 293  | 296  | 306  | 330  | 310  | 301  | 301  | 316  | 318    |
| Primary power         | kW   | 3180 | 2613 | 2844 | 2926 | 2958 | 3059 | 3297 | 3102 | 3008 | 3007 | 3162 | 3176   |
| Engine                |      |      |      |      |      |      |      |      |      |      |      |      |         |
| Operating rate        | %    | 1.00 | 0.92 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99   |
| Real efficiency       | %    | 0.42 | 0.40 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42   |
| Effective power engine| kW   | 1200 | 1054 | 1196 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 | 1200 | 1187   |
| Electricity produced  | MWh  | 806  | 685  | 803  | 780  | 806  | 806  | 806  | 806  | 780  | 806  | 806  | 787    |
| Auxiliary consumption | MWh  | 40   | 34   | 40   | 39   | 40   | 39   | 40   | 39   | 40   | 39   | 40   | 39     |
| Electricity sold      | MWh  | 765  | 651  | 763  | 741  | 765  | 741  | 765  | 741  | 765  | 741  | 765  | 747    |
| Net efficiency        | %    | 0.36 | 0.38 | 0.40 | 0.39 | 0.39 | 0.37 | 0.35 | 0.37 | 0.38 | 0.38 | 0.36 | 0.37   |

This method electricity produced of about 9GWh in 2017, nearly 400 times larger than the energy currently produced on the way out of Manggar landfill. By taking electricity consumption of 800 kWh per inhabitant, it meets the electricity needs of about 10,000 people.

Another option for the Manggar site was trigeneration. An efficient process developed to have a lower consumption of the primary energy and lower GHG emissions is the combined cooling, heating and power (CCHP) system, known as the trigeneration power plants. The principle of operation for a trigeneration system is simple: the heat engine converts the heat taken from a high temperature process into mechanical work achieving a maximum efficiency equal to the Carnot cycle. The heat rejected by the heat engines can be used by another integrated system, improving then the global efficiency [19].

Using the same gas engine as before, it can produce 41.8% of heat (indeed the thermal efficiency is 0.418). Then, by choosing to convert all this heat into refrigerated water with an absorption machine (COPf = 0.7), it can produce 29.3kWh of cold. Since, Indonesia contribute half of the global increase in electricity consumption for air conditioning. Not to mention the network losses, it can be considered this chilled water as much less electricity produced. This increases the overall electrical output of the facility to 71.4% and provides 5,000 more people with electricity. The process efficiency of the trigeneration system is much higher than if the system only used the power produced, but it is lower than if the system used the power and the heat. Because of the cooling demand, the trigeneration system would perform much better economically in a building with a higher cooling load spread over a 12-month period [20].
4. Conclusion

To date, the main role of Manggar Landfill is not to produce biogas but to store Balikpapan City waste. Therefore, the LFC captured installation is not maintained and operated properly. However, a little biogas was used for community consumption and electricity generation for about a hundred families which consume 365kWh of this biogas per year (for 4 people) and that the alternator operates for 2 hours a day, the annual energy generation due to the biogas from the Manggar landfill is therefore 25 MWh maximum.

The potency of LFG is high since more than half percent of waste composition is organic waste which degraded and generated biogas. Based on estimation using LandGEM and Afvalzorg model, Manggar Landfill based on the calculation, in 2017, Manggar landfill produced about 6.44×10^6 m^3CH_4/year by LandGEM model and 5.31×10^6 m^3CH_4/year by Afvalzorg model. The estimated methane then converted to electricity using gas engine and trigeneration methods. Using gas engine, methane from Manggar Landfill is predicted to produce electricity about 787 MWh/month, which equivalent as electricity for about 10,000 people (if considered electricity consumption of 800 kWh per inhabitant).

On the other hand, trigeneration produces 41.8% of heat which convert into 29.3 kWh of cold. Therefore, this increases the overall electrical output of facility to 71.4% and provides 5,000 more people with electricity. In conclusion, it is more beneficial if Manggar Landfill capture and treat its landfill gas particularly methane for generating electricity since Manggar Landfill produces about 6.44×10^6 m^3CH_4/year which can be used for electricity purposes of around 10,000 people using gas engine.

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