ENERGY AND ECONOMIC ANALYSIS OF BIOGAS POWER PLANT FROM MUNICIPAL SOLID WASTE IN INDONESIA

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Abstract

Indonesia is the fourth most populous country with a population of more than 270 million people and is expected to continue to increase. The increasing population has an effect on increasing municipal solid waste (MSW) generation and energy demand. Waste-to-energy (WTE) can be a solution to these two problems. This article will discuss two types of waste-to-energy technology, namely anaerobic digestion and landfill gas recovery. The study began by conducting kinetic modeling on the two technologies to determine the potential of biogas energy produced from municipal waste in Indonesia, the case study applied was Yogyakarta. Then a feasibility study was carried out to find out whether these two technologies are possible to be applied in Indonesia in terms of various aspects such as initial capital costs, operating and maintenance costs, and waste processing service costs. At the end of the study, it was found that biogas power plant with both technology bases was economically feasible. Landfill gas recovery is more attractive because it has a smaller capital and a higher IRR of 22%. The scenario using anaerobic digestion requires a larger capital than the previous scenario and has a lower IRR value of 14%.

Keywords: Biogas, Municipal Solid Waste (MSW), Kinetic modeling, Waste-to-energy (WTE), Feasibility study.

Introduction

Continuous waste generation is a challenge that needs to be overcome with sustainable waste management. There are different way of waste management from the least preferred action which is waste disposal to the most preferred action which is prevention. On average, Indonesian generates 0.76 kg/day of solid waste [1]. It means with more than 270 million population Indonesia generates more than 200 million tonne of municipal solid waste. Unfortunately, the most
common waste management practice in Indonesia is waste disposal in open landfill.

Besides the waste problem, Indonesia also facing an energy challenge. Population growth and rising income per capita have had a big impact on electricity demand. The Electricity Supply Plan [2], basically represents the plan of the state-electricity company PLN’s to provide electricity from the power plant producers. PLN projects electricity demand growth of around 6.86% per annum between 2018 and 2027, reaching a total of 434 TWh of electricity consumed in 2027, compared to 240 TWh in 2018.

Waste to energy (WTE) technologies provides a solution for both waste and energy challenges. WTE refers to the recovery of the energy from waste materials into useable heat, electricity, or fuel [3]. There are different types of WTE technologies with their own characteristics. Different technologies of WTE require feasibility study before applied, include the type and composition of waste, its energy content, the desired final energy form, the thermodynamic and chemical conditions in which a WTE plant can operate, and the overall energy efficiency [4].

WTE technologies can be classified into three types, thermochemical treatment, biochemical treatment, and chemical treatment. In this paper, we will discuss biochemical treatment, which includes anaerobic digestion and landfill gas recovery. Biological WTE technologies are chosen because these technologies will experience faster growth at an average of 9.7% per annum, as new technologies (e.g. anaerobic digestion) become commercially viable and penetrate the market [4].

In this paper, comparison of two scenarios of WTE technology is conducted. The flowsheet of both scenarios is shown in Figure 1. The first scenario is utilization of a biogas power plant using anaerobic digestion to recover energy from municipal solid waste. The second scenario is a biogas power plant using landfill gas as the source of fuel. Energy potential and economic feasibility will be compared in this study.

![Figure 1. Flowsheet of both scenarios](image)

The method to assess the energy potential that can be recovered using both scenarios is kinetic modeling. Biogas modeling is made to analyze and estimate the amount of possible recovered energy. Kinetic model can represent the degradation of the different biodegradable inside municipal solid waste using a simple equation or a set of equations.

Jonathan Rea developed a model of anaerobic digestion using intermediate approach between simple models and complex models [5]. This model can predict the biogas output over time based on the amount of feedstock. The equation used for this model is:

$$C_{\alpha}H_{\beta}O_{\gamma} + \left( n - \frac{\alpha}{4} - \frac{b}{2} \right) H_{2}O \rightleftharpoons \left( \frac{n}{2} - \frac{\alpha}{8} + \frac{b}{4} \right) CO_{2} + \left( \frac{n}{2} + \frac{\alpha}{8} - \frac{b}{4} \right) CH_{4}$$

$C_{\alpha}H_{\beta}O_{\gamma}$ is organic matter with dimensionless coefficients of a, b, and n. The basis of this model is represented by an input output of a well-stirred single tank reactor as shown in Figure 2. The input are reactant A and B with a certain
rate. A and B then broken down into products, C and D. Some of reactant can not be broken down and leaves the digester through outlet.

![Figure 2. Basic input-output model of a well-stirred single tank reactor](image)

Before applying this model, the chemical composition of the organic fraction of municipal solid waste is required. This model considers the amount of carbon, hydrogen, and oxygen as the input. In this study, data from Piyungan landfill in Yogyakarta is used. The chemical composition of the municipal solid waste in Piyungan landfill is shown in table below.

**Tabel 1. Composition of municipal solid waste in Piyungan landfill**

<table>
<thead>
<tr>
<th>Waste type</th>
<th>Mass (ton/day)</th>
<th>Composition (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wet</td>
<td>dry</td>
</tr>
<tr>
<td>Garden</td>
<td>201</td>
<td>6</td>
</tr>
<tr>
<td>Food</td>
<td>129</td>
<td>6</td>
</tr>
<tr>
<td>Plastic</td>
<td>43.2</td>
<td>39.3</td>
</tr>
<tr>
<td>Textile</td>
<td>24</td>
<td>21.8</td>
</tr>
<tr>
<td>Rubber</td>
<td>14.4</td>
<td>13.1</td>
</tr>
<tr>
<td>Wood</td>
<td>67.2</td>
<td>33.6</td>
</tr>
</tbody>
</table>

Source: Sudibyo, 2016

There are some limitations of to this model.
- Kinetic constant (k) is not affected by temperature change
- Atypical waste composition
- Value of k and waste composition are constant over time

In the second scenario the model used for landfill gas generation is based on a software developed by United States Environmental Protection Agency (EPA), LanGEM. This model uses a first-order decomposition rate equation to predict annual methane generation from a landfill [6].

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k Lo \left( \frac{M_i}{10} \right) (e^{ktij})$$ (2)

Where
- Q: gas generation flowrate (CH$_4$)
- i: a one-year time increment
- y: year of the calculation
- j: 0.1-year time increment
- k: constant of methane generation rate
- Lo: potential methane generation
- Mi: mass of waste disposed in the i-th year
- tij: age of the jth section of a waste of as disposed of in the i-th year

This model assumes that the peak of methane generation is shortly after initial waste placement, then decrease exponentially [7]. There are some limitations of this model.
1. Landfills that have methane content out of the recommended range (40 to 60 percent) is less accurate
2. Atypical waste composition
3. Value of k and Lo are constant over time

After done with biogas generation modeling, economic analysis is conducted. The purpose of this analysis is to know the feasibility of both scenarios to be applied in Indonesia and provide comparison between both technologies by calculating the net present value (NPV) and internal rate of
return (IRR). There are some general assumptions made for both scenarios.
1. The lifetime of the plant is 20 years
2. The cost of waste is zero and waste feedstock is always available
3. The selling price of electricity is USD 13.35 cents/kW [8]
4. Zero tipping fee (according to Presidential Regulation No. 35/2018 the range of tipping fee is 0 to 500,000 IDR)
5. Weight cost of capital is 10%
6. Plant size is 5 MW and will be varied from 1 to 11 MW in the sensitivity analysis
7. Plant capacity is 7500 hours/year
8. Variation of initial capital cost and O&M cost are taken from IRENA [9].

Result and Discussions

This section will discuss the results of biogas modeling of both model, anaerobic digestion model and landfill gas generation model. After that the results of economic analysis will be shown and compared. Lastly, sensitivity analysis will be conducted by varying some parameters.

**Biogas Generation Model**

The assumption for plant size is 5 MW and 7500 hours/year capacity.

\[
5MW \times \frac{7500h}{y} = 37500 \text{ MWh/year}
\]

The typical value for thermal power plant efficiency is 36% (IRENA, 2012),

\[
37500 \text{ MWh/year} \div 0.36 = 104166.67 \text{ MWh/y}
\]

and the heating value for methane is 13.9 kWh/kg, so the required amount of methane gas as the source of fuel is

\[
\frac{104166.67 \text{ MWh}}{y} \div \frac{13.9 \text{ kWh}}{kg} = 7494004.79 \text{ kgCH4/year}
\]

if consider the amount of CH4 needed each month, the plant require 624500 kgCH4/month.

After knowing the amount of methane required in each month we adjust the amount of waste input, to satisfy the required amount of methane. Figure below is the results of kinetic modeling of anaerobic digestion. The input of this model is 93 Mg of organic waste which composition shown in table 1.

![Figure 3. Anaerobic digestion model](image_url)

As shown in Figure 3, the generation of CH₄ and CO₂ start in the matter of days until reach its peak after two weeks. Note that this case does not necessarily represent the real system of anaerobic digestion, the plant could have more than one digester. For 93 tons input of organic waste, the methane generated is around 625000 kgCH₄. If we compare the amount of waste input each month, which is 93 ton, with the waste generation in a small city like Yogyakarta, which is 360 ton everyday based on Ministry of Environment and Forestry, the supply of waste is abundant.

In the second scenario, landfill gas generation modeled for the whole lifetime of the plant, which is 20 years. In this model we also adjust the amount of waste so it can satisfy the required amount of methane.
We can see in Figure 4 there are two lines, red and blue. The red lines represent the trend of methane generation in each batch of waste input. This model assumes that each batch of waste input happen once in a year. However, this assumption is different from the real practice. The model also assumes that the methane generated is going to reach the peak within the first year after waste input then slowly tapers off. The blue line is the accumulation of the red line, which is the total amount of methane generation for a whole lifetime. In this scenario the amount of waste input in each month to satisfy the required amount of methane is 11 ton.

If we compare both of the model, the required amount of waste input needed in the second scenario is much lower than the first. However, the first scenario, anaerobic digestion, has shorter amount of time to reach the peak of methane generation. Anaerobic digestion needs two weeks to reach the peak of methane generation while landfill gas generation model needs a year to reach its peak.

We can say that anaerobic digestion is more flexible because it is easier to control the amount of methane generation. On the other hand, landfill gas recovery offers simplicity, because of lesser amount of waste to handle and the technology used is much simpler.

**Economic Analysis**

In this section we will show the comparison of economic indicators for both scenarios. Some parameters are set to be the same value for both scenarios to have a fair comparison, such as plant size, annual capacity, electric efficiency, electricity tariff, and tipping fee.

<table>
<thead>
<tr>
<th>Table 2. Economic Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Plant</strong></td>
</tr>
<tr>
<td>Size</td>
</tr>
<tr>
<td>Availability</td>
</tr>
<tr>
<td>Tariff</td>
</tr>
<tr>
<td>Tipping fee</td>
</tr>
<tr>
<td><strong>Production/Processed</strong></td>
</tr>
<tr>
<td>Organic waste</td>
</tr>
<tr>
<td>CH4</td>
</tr>
<tr>
<td>Electric Efficiency</td>
</tr>
<tr>
<td>Electricity</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
</tr>
<tr>
<td>Capital Cost</td>
</tr>
<tr>
<td>O&amp;M Cost (fixed)</td>
</tr>
<tr>
<td>O&amp;M Cost (variable)</td>
</tr>
<tr>
<td><strong>Profit</strong></td>
</tr>
<tr>
<td>Electricity selling</td>
</tr>
<tr>
<td>Tipping Fee/year (maximum)</td>
</tr>
<tr>
<td><strong>Indicators</strong></td>
</tr>
<tr>
<td>Annual profit before tax</td>
</tr>
<tr>
<td>Annual profit after tax</td>
</tr>
<tr>
<td>NPV</td>
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<tr>
<td>IRR</td>
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</tbody>
</table>
From table 2, we can say that both scenarios are feasible to be applied in Indonesia. For the same plant size, landfill gas recovery system will have lower capital cost since its capital cost per kWh is lower than anaerobic digestion. However, for the operation and maintenance (O&M) cost, anaerobic digestion has lower cost compared to landfill gas recovery system. Both of the O&M cost are a function of its capital cost. Although the capital cost of anaerobic digestion is higher, the multiplier for O&M cost is lower than the other. Besides that, the O&M cost of anaerobic digestion is also a function of its electricity generated. In the end the total annual cost of opertaion and maintenance is lower for the first scenario.

There are two incomes taking into account in the analysis, electricity selling and tipping fee. Both are regulated in Presidential regulation 35/2018. Tipping fee is paid by government to the party that manage waste. Based on the regulation the maximum tipping fee is IDR 500,000 per tons of waste. However, in this study it is assumed to be zero since the fact that inconsistent policy is often occurred and the regulation does not set the minimum value of tipping fees.

Both scenarios have positive NPV, which means they are considered to be financially profitable undertakings. The annual profit is higher in the first scenario, but the NPV is higher for landfill gas recovery system due to its lower capital cost. The value of IRR of both scenarios are higher than its WACC, which indicates the financial profitability of both scenarios.

**Sensitivity Analysis**

In the first scenario, some input parameters will be varied to see the change in NPV. The parameters that varied are plant size, electricity tariff, and capital cost, which will also affect O&M cost. Plant size is ranged from 1 MW to 11 MW with 2.5 MW increment. The electricity tariff is ranged from USD 8 cent/kWh to USD 16 cent/kWh. Lastly, the capital cost is varied from USD 2000/kW to USD 6000/kW.

As shown in Figure 5, NPV has a positive relationship with electricity tariff. Net present value is higher when the electricity tariff increase. On contrary, the increase in capital cost has negative effect on NPV. And the variation of size is amplifying the effect of capital cost and electricity tariff changes.

If we see the graph carefully, there is a line that separates the region of positive and negative NPV. The line can be written as equation.

\[
\text{Capital cost} < 38147.965 \times \text{tariff} - 239.24 \quad (3)
\]

In the scenario, the parameters that varied are plant size, electricity tariff, and O&M cost. Plant size is ranged from 1 MW to 11 MW with 2.5 MW increment. The electricity tariff is ranged from USD 8 cent/kWh to USD 16 cent/kWh. Lastly, the O&M cost which is a function of capital cost is varied from 11% to 19% of capital cost. This variation is based on International Renewable Agency.
As shown in Figure 6, NPV has a positive relationship with electricity tariff. Net present value is higher when the electricity tariff increase. On the other hand, the increase in operation and maintenance cost has negative effect on NPV. And the variation of size is amplifying the effect of O&M cost and electricity tariff changes.

In this graph we also can see a line that separate NPV into positive and negative region. This line can be written as

\[ O&M\ cost < 2.816 \times tariff - 0.1178 \] (4)

**Conclusion**

In this study, two types of WTE technology are compared based on an energy potential and economical point of view. The first scenario is a 5 MW biogas power plant that utilize anaerobic digestion to recover energy from municipal solid waste. The second, is also a 5 MW biogas power plant using landfill gas as a source of fuel.

Anaerobic digestion requires more waste as the input compared to landfill gas recovery system. However, anaerobic digestion is more flexible because it is easier to control the amount of methane generated. Anaerobic digestion reaches its peak of methane generation in two weeks, while landfill gas model in one year.

In economic analysis, both scenarios are economically feasible. Both of them have positive value of NPV. The value of internal rate of return in both scenario is higher than WACC, which indicates both scenarios are financially profitable undertakings.

In the future study, biogas modeling can be improved by using a more comprehensive model to get a better and more accurate result. This will require more data of waste and the characteristic in specific region chosen.

**Daftar Pustaka**


[6] Landfill Methane Outreach Program. LFG Energy Project


[8] Peraturan Presiden Nomor 35 Tahun 2018