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LCA of Biogas Through Anaerobic Digestion from the Organic Fraction of Municipal Solid Waste (OFMSW) Compared to Incineration of the Waste

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Abstract

Production of biogas through anaerobic digestion (AD) from the organic fraction of municipal solid waste (OFMSW) was compared to incineration of the waste. At the moment, almost all of the OFMSW in Singapore is incinerated. Three different scales of biogas plants were compared to incineration: one large-scale biogas plant that can treat half of all OFMSW in Singapore; one medium-scale biogas plant about 15 times smaller than the large one; and one small-scale biogas plant that can treat waste from e.g. a shopping centre or food centre. Two alternatives for utilization of the biogas were also compared, generation of electricity and the use of the biogas in heavy vehicles. The combination of the different scales and the different utilization gives the six different scenarios. By using life cycle assessment (LCA) the different scenarios were compared in terms of global warming potential (GWP), acidification, eutrophication, energy use and land use. The results show that biogas production creates less environmental impact than incineration. The use of the gas as a vehicle fuel creates a bigger decrease of GWP, acidification and eutrophication than when using the gas for electricity generation. The prevention of leakage of biogas during production and upgrading is crucial for the environmental impact on GWP. A leakage of only a few percent of the produced gas will lead to a loss of all the gain in saved GHG-emissions.

Key words: Biogas, OFMSW, MSW, LCA, Anaerobic Digestion

1. Introduction

Singapore has one of the highest populated countries in the world, with a population of about 4.8 million people on a land area of only about 710 km² [1]. The population has grown by almost one million from 1998 to 2008. Singapore has had a tremendous and almost constant economic growth since the land gained sovereignty in 1965. The high population density in combination with rapid economic growth has made waste management a very important issue for the country.

Currently, most of the non-recyclable Singapore waste is incinerated and the remaining ashes is sent to an off-shore landfill. Almost all of the recycled waste originates from non-domestic sources, while many of the typical domestic waste streams have very low recycling rates; for example, only 9% of the food waste is recycled, while the rest is incinerated [2].

Due to the lack of suitable land to open new landfills, and the great cost of building new incineration plants, the government of Singapore has adopted a strategy to make its waste management system sustainable. The two main targets are:

- Towards Zero Landfill
- Achieve 60% Recycling Rate by 2012

To reach these goals, the government is currently working with three main strategies: waste reduction, waste recycling and minimizing landfill use through incineration [5]. When incinerating the waste the volume can be reduced by 90%, but there is still ash that has to be landfilled; this is why the recycling and reprocessing of waste is so important. When it comes to the organic fraction of municipal solid waste (OFMSW), production of biogas through anaerobic digestion (AD) can be used with good results. An argument in favour of using AD versus other treatments such as landfilling, composting or incineration is that if organic waste is landfilled, it would lead to a large amount of methane emitted to the air due to uncontrolled anaerobic digestion. Incineration of organic waste is energy consuming due to the high moisture content of the waste; it also generates ash that must be landfilled, and composting might also cause emissions of methane.

Anaerobic digestion has also been considered a good treatment for organic waste because of the biogas it produces, which can be used as a vehicle fuel or for electricity and heat depending on the demand. The residue from AD is often used as a fertilizer or soil improver, bringing back important nutrients to the soil.

When using AD, all products from the process can be used and no material must be landfilled, which is in line with the Singapore’s “Towards Zero Landfill” strategy.
2. Objective

The aim of this project was to investigate if production of biogas from the organic fraction of municipal solid waste (OFMSW) is sustainable in Singapore, from an environmental point of view. The main research questions were:

- **RQ1** – Is biogas production of OFMSW in Singapore a better alternative than incineration?
- **RQ2** – What scale of biogas plant results in the least environmental impact?
- **RQ3** – What are the key processes that cause the most environmental impact in the different scenarios?

3. Method

The current handling of the OFMSW was compared in 6 different scenarios where biogas is produced from the OFMSW. A life cycle assessment (LCA) was conducted to compare these 6 scenarios. In the study, the different alternatives were compared in terms of global warming potential (GWP), acidification, eutrophication, energy use and land use; emission of toxic substances was not included in the study.

To prevent sub-optimization, a LCA includes all processes from cradle to grave. This was the main reason why LCA was used in this study, since the waste management system includes many processes and comparing e.g. only the biogas plant and the incineration plant would probably give misleading results. However, a LCA is always a study of the environmental impacts from the processes inside the system boundary that have been set with respect to the goals. It is important to remember that all environmental impacts, from a product or service, can never be considered [6].

The study was divided into two parts. In the first part, three different scenarios where biogas from OFMSW is used for electricity generation were compared to incineration of the OFMSW. In the second part, the three biogas scenarios were producing vehicle fuel. Since the goal of this project was to study and compare alternative ways to manage the OFMSW, the functional unit was 1 ton of OFMSW.

3.1. Biogas used for electricity generation

In order to take into account indirect environmental impacts (Avoidance of potential environmental impacts), the output of electricity and fertilizer has been set to the same amount for all the scenarios. For example, the incineration scenario does not produce any fertilizer, while the production of inorganic fertilizer has been added to the system. The output of electricity and fertilizer is 434 kWh/FU of electricity, 6.3 kg/FU of nitrogen and 3.3 kg/FU of phosphate. Below is a short description of the scenarios in Part 1:

3.1.1. Ref 1 – The current management of OFMSW in Singapore. Waste is transported from the citizen or facility to one of four existing incineration plants. From the incineration plant, the ash is transported by truck and barge to a landfill on Semakau Island, about 25 km from the Singapore coast. The processes in this scenario are: transportation of waste to incineration plant, incineration (included combustion and plant operation), and transportation of ash to landfill. Methane leakage from the landfill is not included in this study, since the leakage of methane from Semakau landfill is minimal [7]. To make the output from all scenarios equal, production of inorganic fertilizer has been added to the incineration scenario for the same reason electricity from natural gas has been added to the scenario: so that all the scenarios will produce the same amount of electricity.

3.1.2. Large 1 – A large-scale biogas plant that can treat half of all OFMSW in Singapore. First, the OFMSW is transported to the plant where it is processed and the resulting biogas is used to generate electricity. The by-product from the digestion is then composted and sold as soil improver. The processes in this scenario include: transportation of OFMSW to biogas plant, pre-treatment, AD, dewatering, and transportation of compost. Finally, the wastewater is led back into the bio reactor; thus, there is no reason to explore wastewater treatment in this study.

3.1.3. Medium 1 – A medium-scale biogas plant about 15 times smaller than the large one. Here, the OFMSW is transported to several mid-scale biogas plants where it is processed. The processes included are the same as for scenario Large 1, but electricity generation from natural gas has been added to the scenario since this mid-scale plant generates less electricity than scenario Large 1.

3.1.4. Small 1 – A small-scale biogas plant that can treat waste from e.g. a shopping centre or a food centre. These plants are not meant to take care of all the OFMSW in Singapore. The OFMSW is disposed directly into the plant, meaning no collection or transportation of the OFMSW is needed. The processes included in this scenario are: pre-treatment, AD, dewatering, and transport of compost. To make the output from this scenario the same as for the other scenarios, electricity generation from natural gas has been added.

3.2. Biogas as a vehicle fuel

In this second part, the biogas is used as a vehicle fuel in the system instead of using it to generate electricity.
This is to determine if this usage alternative is more environmentally friendly than to be used in generation of electricity. The indirect environmental impacts have been taken into account in the same way as in the Part 1. The amount of diesel avoidance from the biogas production is added to the incineration scenario. The output of each scenario is set at 171 kWh/FU of electricity, 6.3 kg/FU of nitrogen, 3.3 kg/FU of phosphate and 1036 kWh of vehicle fuel. Below is a short description of the different scenarios:

3.2.1. Ref 2 – The only difference between this scenario and Ref 1 is that the indirect environmental impacts are different. The indirect environmental impacts come from production of fertilizer and use of diesel in heavy vehicles.

3.2.2. Large2 – This scenario includes the same processes as Large 1, but upgrading of the gas has been added. This is necessary for the biogas to be used as vehicle fuel. During the upgrading of the biogas, electricity needed for the biogas production must be taken from the grid instead. This leads to increased emissions of fossil CO₂ and other emissions such as NOₓ and SO₂. In this scenario, some of the biogas produced is combusted in a furnace to heat the biogas reactor, which makes the net output of biogas smaller. The indirect environmental impacts is contributed by the generation of electricity from natural gas.

3.2.3. Medium 2 – This scenario includes the same processes as Medium 1, but upgrading of the gas has been added. The indirect environmental impacts come from the generation of electricity from natural gas.

3.2.4. Small 2 – This scenario includes the same processes as Small 1, but upgrading of the gas has been added. The indirect environmental impacts come from the generation of electricity from natural gas and use of diesel in heavy vehicles, since this scenario is unable to produce as much biogas as L 2 and M 2.

The reference scenario is based on data of the current waste management system in Singapore [4, 7, 8, 9]. The biogas scenarios are models which are not based on any real biogas plants in specific. In all the biogas scenarios, the biogas is produced through a one-step process, under thermophilic conditions. This is because the thermophilic process is more effective, since the mean temperature in Singapore is high, thus the additional heat needed for heating the substrate to the required temperature is relatively lower, even with a thermophilic process. Detailed information on inventory data and references to this data can be found in the report that this paper builds on [10].

The digestate is assumed to be dewatered and composted after the digestion step. This is mainly because the demand for fertilizer in Singapore is not high, which means that the digestate has to be exported to other countries e.g. Malaysia. By dewatering and composting the transport of the compost material that is not used in Singapore, it is more profitable as it has a higher dry matter content. By composting the digestate it is further decomposed, which also reduces the overall volume of the material. Another important reason for dewatering the digestate is to minimize the use of fresh water, since water is a scarce commodity in Singapore. By dewatering and leading back this water into the bioreactor, the use of fresh water will be as low as possible.

4. Results

While full results from the study can be found in [10], below is a summary of the most significant.

In Figures 1-3, the decrease in environmental impact when producing biogas versus incinerating the OFMSW is shown. The impacts are smaller for all the biogas scenarios than for the reference scenarios. However, when using the biogas for electricity generation, the decrease in acidification and eutrophication are quite small.

Figure 1 shows the impacts of leakage of methane from the biogas plant. Figure 4 is based on scenario Large 1. In the study, the leakage of methane is assumed to be 1% of the produced gas. Figure 4 shows that if the leakage is 1%, the difference in GWP between Ref 1 and Large 1 is substantial. However, if the leakage of methane is more than 7% of the produced gas, all the positive gain in GWP is lost.

![Figure 1 Decrease in GWP for the different biogas scenarios compared to the reference scenarios [10].](image-url)
5. Discussion and conclusion

Like in all other LCA, the results here is only valid for the system boundaries that have been set for this study. With changed system boundaries, the results might have been completely different. A source of uncertainty in the results is the data quality. In this study, a large part of the data comes from foreign literature and facilities outside Singapore, which means that the data is accurate and valid from a Singapore context only to a certain extent. However, there is still reason to believe that the results of the study are valid and reflective, since a lot of the data need not be site-specific. The main reason for the lack of data from Singapore specifically is because the only AD plant in Singapore is only in operation in the last few years and there is not yet a proper study or data collection process being carried out for this purpose. There are some efforts on going and in future, these data can be used in similar LCA like this.

5.1. Biogas used for electricity generation

With the system boundaries given in this study, production of biogas from OFMSW is a better option than incineration. For example, the reference scenario gives about 130 kg more CO₂-eq/FU than the medium and large-scale scenarios and about 80 kg CO₂-eq/FU more than the small-scale scenario. The higher GWP from the reference scenario is mainly due to the indirect environmental impacts, which is the production of fertilizer and generation of electricity from natural gas. Thus, the reason why the incineration plant has higher GWP is low conversion efficiency, and that the scenario does not make use of the waste in a way that everything is recovered. For acidification the large, medium and small biogas scenarios generate about 130 g SO₂-eq/FU, 140 g SO₂-eq/FU and 160 g SO₂-eq/FU less than the reference scenario, respectively. However, the biogas scenarios and incineration had about the same impact on eutrophication, and the biogas scenarios had only about 8 g PO₄³-eq/FU -15 g PO₄³-eq/FU lower eutrophication than the reference scenario, which is because the combustion of biogas gives high emissions of NOₓ.

From the results, it shows the utmost importance to prevent leakage of methane at biogas plants. Methane leakage has a very big impact on the GWP from biogas systems. When biogas is leaking, methane alone can predominantly determine the GWP of the biogas system. Therefore, leakage of biogas must be controlled and carefully monitored at a biogas plant.

When it comes to energy use, the incineration plant uses the most electricity and has a lower electricity output than all of the biogas plants. The net output of electricity from incineration of OFMSW is only about 40% of that from the large or medium-scale biogas plants. The small-scale biogas plant also has a much higher electricity output than the reference scenario. However, the data on electricity use at the small-scale plant is a quite uncertain figure, since the data actually comes from farm-scale biogas plants handling e.g. straw, not OFMSW.

Due to the unavailability of electricity usage data when producing fertilizer, only the electricity usage at the plants is included. There is data that shows that there is
quite a large amount of energy used when producing fertilizer [11, 12], but the data did not specify the source of the energy.

Of the biogas scenarios, the small-scale scenario has the highest use of heat energy. The small biogas plant uses about 1.7 times more heat than the medium and large-scale plants. This is probably due to poor insulation at a small-scale facility. In Singapore, the heat usage is not a big issue, since waste heat is not usually sold. In order to improve the heat usage and reduce the environmental burden, a new biogas plant can be strategically placed near an industry that is in need of steam, so that the waste heat can be captured for reuse.

A large or medium-scale facility seems to be preferable to a small-scale facility. Small-scale biogas plants are inefficient, and probably too land-consuming for Singapore. Small-scale biogas plants would probably be a good alternative when the transport distance of the waste to a centralized plant is very long, and in the case of no lack of land area to build on. In Singapore, the transport distances will always stay quite short because of the small land area. In cold climate areas where there is a demand for heat, a small facility can be utilized in a better way as all the waste heat can be used directly for heating instead of converting to electricity, which has a low conversion efficiency.

5.2. Biogas as a vehicle fuel

In this study the biogas scenarios also had less environmental impact than the reference scenario, for all emission categories. The difference between the biogas scenarios and the reference scenario was bigger here than in Part 1. This means that, in terms of emissions, it is better to use the biogas as vehicle fuel in heavy vehicles (replacing diesel) than for electricity generation (replacing incineration of OFMSW and natural gas). This is mainly because the diesel used in the reference scenario gives high amounts of emissions. Even though both diesel and natural gas are fossil fuels, diesel has higher emissions of GHG, NOx and SOx. In this case, the reference scenario also gives about 130 kg CO2-eq/FU more than the biogas scenarios. For acidification and eutrophication, however, the difference is big. The reference scenario generates about 2 kg SO2-eq/FU more than the three biogas scenarios, and about 0.2 kg PO43-eq/FU more than the three biogas scenarios. If only GWP is considered, the biogas can be used either for electricity generation or as a vehicle fuel. However, if acidification and eutrophication are considered, then the use of the gas as a vehicle fuel gives lower environmental impacts. The differences in GWP, acidification and eutrophication are larger in this study than in the original study, and it seems that the use of biogas as a fuel for heavy vehicles is a better option than using it for electricity generation. Other studies have shown similar results, i.e. that biogas is best utilized in vehicles [13, 14].

One issue that exists in both Parts 1 and 2 is the leakage of methane. If the leakage of methane gets too big, the positive gain in GWP when using AD instead of incineration is lost. Upgrading usually causes higher losses of gas than the production of the gas, which is why the upgrading plant must be monitored carefully together with the biogas plant.

Another issue with the use of biogas in vehicles is the distribution of the fuel. In Singapore there are already some buses running on compressed natural gas (CNG); in these buses, upgraded biogas might as well be used. As Singapore strives to keep emission levels down on a local level, hence not only GWP should be considered. The use of biogas in vehicles will most probably reduce emissions of particulates (PM2.5 & PM10), since diesel produces 11 particulates/MJ fuel and biogas less than 0.002 particulates/MJ fuel [15]. Thus, the use of biogas in heavy vehicles, such as buses, might help significantly to achieve cleaner air in Singapore.

This study gives an overall view on how OFMSW can be treated in Singapore, but more detailed research in several areas is needed. Since the leakage of methane is a very important issue at biogas plants, studies should be done on both how much gas is leaking from biogas plants and also in the processes the leakage might possibly takes place. Another area that needs further investigation is the composition of the OFMSW in Singapore. This can help to predict biogas yields and determine how to run the biogas reactor in an optimal way. In many countries the OFMSW is co-digested with sewage sludge, which could be an interesting alternative for Singapore.

In order to evaluate if biogas production could be feasible in Singapore from an economic perspective, an economic assessment should be done, where biogas production is compared to the current treatment by incineration. There is also a need to come up with effective ways or take back network to collect the organic waste and to encourage citizens to source sort their organic household waste. This is very important since source sorting of the waste is necessary to make any treatment of OFMSW efficient and effective.

5.3. Concluding remarks

The conclusions from this study can be summarized in five bullets:

- Production of biogas appears to be a better option than incineration.
- Production of vehicle fuel is a better utilization of biogas than electricity generation.
• Leakage of biogas must be controlled and carefully monitored at the biogas plant
• A medium or large-scale plant is better than a small-scale plant.
• The reason why most of the biogas scenarios give less environmental impact is the indirect environmental impact from incineration when the scenarios are compared, since the biogas scenarios generally are more effective and can replace more fossil fuels.

6. References


