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Environmental impact assessment of energy recovery from food waste in Singapore

– Comparing biogas production to incineration

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Abstract

As a small and land scarce country, effective waste management is of outmost importance in Singapore. In this study the production of biogas through anaerobic digestion 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 scenarios were compared to the reference scenario (incineration): one with a large scale biogas plant that can treat half of all OFMSW in Singapore, one with a medium scale biogas plant about 15 times smaller than the large one and one with a small scale biogas plant that can treat waste from e.g. a shopping center or a food center.

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. Two alternatives for utilization of the biogas were also compared through LCA, generation of electricity and the use of the biogas in heavy vehicles.

From an environmental perspective production of biogas is a better way to treat OFMSW than incineration. When biogas is used for electricity generation the impact on GWP decreased about 80-130 CO_2-eq/ton compared to the incineration scenario and also has lower impact on acidification and eutrophication. The result also showed that the use of the gas as a vehicle fuel gives about the same impact on GWP as when the gas is used to generate electricity but a much lower impact on both acidification and eutrophication. In terms of scale, the medium and large scale plants have less environmental impact than the small scale plant when the gas is used as a vehicle fuel. When the gas is used to generate electricity, the small scale scenario had higher GWP but lower acidification and eutrophication.

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 green house gas emissions.

Sammanfattning

Bedömning av miljöpåverkan från energiutvinning ur organiskt hushållsavfall i Singapore – en jämförelse mellan biogasproduktion och förbränning

Singapore är ett litet och tätbefolkat land med en växande befolkning. På grund av detta har frågan om hur landets sopor bäst ska tas om hand blivit allt viktigare. Det beror mycket på att det inte längre finns någon lämplig yta att anlägga deponier på och att uppförandet av nya förbränningsanläggningar har visat sig väldigt kostsamt. Av det avfall som återvinns i Singapore kommer nästan allt ifrån industrin. För hushållssopor och sopor från restauranger och shoppingcenter är återvinningsgraden väldigt låg. Av det matavfall som genereras återvinns bara ca 9%[1], resten hamnar i någon av de fyra förbränningsanläggningarna som finns i Singapore.

Målet med detta projekt var att undersöka om det skulle vara miljömässigt motiverat att tillverka biogas från det organiska avfallet i Singapore, istället för att forbränna det. Dessa två alternativ jämfördes med hjälp av livscykelanalys (LCA). I studien inkluderades påverkan på växthuseffekt, försurning och övergödning samt energianvändning och markanvändning.

Fyra olika alternativa sätt att behandla det organiska avfallet i Singapore jämfordes i studien:

- Förbränning av det organiska avfallet, i någon av de fyra förbränningsanläggningarna.
- Tillverkning av biogas i en storskalig anläggning som kan ta hand om hälften av det organiska avfallet i Singapore.
- Tillverkning av biogas i en medelstor anlägging som kan ta hand om 21000 ton avfall per år och är ungefär 15 gånger mindre än den stora anläggningen.
- Tillverkning av biogas vid en småskalig anläggning som endast tar emot 800 ton avfall per år. Denna anläggning kan ta hand om avfall från ett shoppingcenter eller ”food court”.

I alla scenarier ingick insamling av avfallet och transport av avfall och restprodukter. Indirekta miljöeffekter har också inkluderats i beräkningarna.

[1] MEWR (2007), solid waste management.

Två olika alternativ för användning av biogasen jämfördes också, elproduktion och användning av biogasen i tunga fordon.

Studien visade att tillverkning av biogas är bättre än förbränning av avfallet. När biogasen användes för elgenerering minskar påverkan på växthuseffekten med 80-130 CO_2-ekv/ton, beroende på vilken skala det är på anläggnigen. I fallet med elgenerering minskar påverkan på försurning med 130-160 g SO_2-ekv/ton, påverkan på övergödning minskar dock ytterst lite och är ungefär den samma som för förbränningsalternativet. När biogasen används som fordonsbränsle minskar påverkan på växthuseffekten med drygt 130 CO_2-ekv/ton och för försurning och övergödning så minskar påverkan drastiskt. Försurningen miskar med drygt 2 kg SO_2-ekv/ton och drygt 200 g PO_4^{3-}-ekv/ton. Utsläppen minskar alltså mer när biogasen används som fordonsbränsle än när den används för elgenerering. Dock används mer electricitet per ton avfall i fallet när biogasen uppgraderas till fordonsbränsle.

Studien visar att läckage av biogas från produktion och uppgradering är mycket viktig att förhindra eller begränsa. Ett läckage av 5-9 % av den producerade gasen gör att hela minskningen av växthuseffekt äts upp av metanautsläppen, och att metan helt dominerar utsläppen av växthusgaser.

Terminology

Acidification – When the input of hydrogen ions to water or soil is greater than what can be neutralized. This leads to a too low pH value in the water or soil.

Anaerobic digestion – Biological decomposition of organic matter in absence of oxygen. During the process biogas is formed.

Auxiliary oil burner – Oil burner that is used to start up the combustion of the waste at the incineration plant.

Biogas – Gas that is formed during anaerobic digestion, consists mainly of methane and carbon dioxide.

Bio reactor – The tank where the anaerobic digestion is performed.

Biogas yield – The amount of biogas that can be formed from a substrate, usually per weight unit. The term sometimes refers to the methane yield, see “methane yield”.

Characterization factors – Factors to aggregate all emissions from one impact category to one number.

C:N ratio – Tells the ratio between carbon and nitrogen in the soil. Is an indicator of eventual nitrogen limitation for plants and organisms.

Dioxins – Usually refers to polychlorinated dibenzodioxins (PCDDs). Compounds that are accumulated in fatty tissue in humans. They cause negative effects on reproduction, sexual development and the immune system. There are indications that they might cause cancer.

Direct environmental impact – Environmental impacts that originate directly from the product or service studied in an LCA.

DM – Dry Matter

Eutrophication – When water such as lakes or streams receive excess nutrients that stimulate excessive plant growth. When plants die and decomposes the dissolved oxygen in the water is reduced and this causes other organisms to die.

Fertilizer – Compounds that are applied to the soil to promote plant growth. The three main compounds are nitrogen, phosphorus and potassium.

Furans – Compounds that cause similar damage to human health as dioxins.

GHG – Green House Gases

GWP – Global Warming Potential

Indirect environmental impact – Environmental impacts that occurs as a consequence of a product or service, but does not come from the life cycle of the product or service it self.

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization of Standardization

LCA – Life Cycle Assessment

Mesophilic digestion process – Anaerobic digestion at about 35 °C-40 °C.

Methane yield – The amount of methane gas that can be formed from a substrate, usually per weight unit.

Moving grate incinerator – A moving grate moves the waste through the furnace, to allow more efficient and complete combustion.

OFMSW – Organic Fraction of Municipal Solid Waste

Soil improver – Is a material added to the soil to correct the deficiencies of the soil. It can both add nutrition to the soil and help the soil to hold more water.

Thermophilic process – Anaerobic digestion at about 55 °C.

Upgrading – Cleaning biogas from impurities, mainly CO_2, to get the same quality as natural gas.

1 Introduction

Singapore has one of the highest population densities in the world, with a population of about 4.8 million people and a land area of only about 710 km^2[2], and 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 a rapid economic growth has made waste management a very important issue for the country.

Until 1979 all waste were disposed in land fills, but to make the waste management system less dependent on land fills an incineration plant was built in Ulu Pandan. After that, three other incineration plants have been built and together the four plants incinerate about 43% of the total waste generated, while 54% is recycled and 3% is sent directly to land fill.[3]

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.[4]

Due to the lack of land where it is possible to open new land fills, and the great cost of building more incineration plants, the Singapore government has adopted a strategy in order to make the waste management system sustainable. The two main targets are:

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

To reach these goals one is currently working with three main strategies: waste reduction, waste recycling and minimizing landfill use through incineration.[5]

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[2] Statistics Singapore (2008). Key Annual Indicators.
[3] MEWR (2007), solid waste management.
[4] MEWR (2007), solid waste management.
[5] MEWR (2007), clean land.

When incinerating the waste the volume can be reduced by 90%, but there is still ash that has to be land filled. This is why 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, the arguments in favor of using AD instead of other treatments such as land filling, composting or incineration could be that if organic waste is land filled, there will be a large amount of methane emitted to the air due to uncontrolled anaerobic digestion. Incineration of organic waste is energy consuming because of the high moisture content in the waste and also generates ash that has to be land filled, composting might also cause emissions of methane.

Anaerobic digestion has been considered a good treatment of organic waste also because of the product biogas, 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 fertilizer or soil improver and brings back important nutrients to the soil.

When using AD all products from the process can be used and no material has to be land filled, which is in line with the Singapore “Towards Zero Landfill” strategy.

1.1 Objective

This project aims to investigate if production of biogas from the organic fraction of municipal waste (OFMSW) is sustainable in Singapore, from an environmental point of view.

The current handling of the OFMSW will be compared to three scenarios where biogas is produced from the OFMSW using life cycle assessment (LCA). In the study the different alternatives will be compared in terms of global warming potential (GWP), acidification, eutrophication, energy use and land use. Emission of toxic substances will not be included in the study.

1.2 Life cycle assessment

The life cycle assessment methodology (LCA) is used to determine what impact a product or a service has on the environment. The methodology evolved because there was a need to regard the whole lifecycle of a product when examine the environmental impacts, instead of just looking into one process at the time. When only dealing with one process at the time, the improvement in one area might lead to enhanced environmental impact in another. To prevent this phenomenon, called sub optimization, an LCA includes all processes from cradle to grave. However, an LCA is always a study of the environmental impacts from the processes inside the system boundary that has been set for the study. It is important to remember that all environmental impacts, from a product or service, can never be considered .[6]

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[6] Rydh et al. (2002)

2 Background

2.1 Refuse incineration in Singapore

The four incineration plants in Singapore are moving grate incinerators. Before incineration the waste is stored in a bunker. From the bunker the waste is fed into the furnace by grab-cranes. The waste is moving through the furnace on a grate while the furnace is fed with hot air through the grate in order to dry the waste and make it burn more easily. The air is taken from the bunker and heated by steam before entering the furnace. This makes the pressure in the bunker lower than atmospheric pressure and prevents odor from escaping the bunker. The ash and slag from the combustion is transported to an ash pit and from there transported to a land fill. Ferrous materials are sorted out by electromagnets and sent to recycling facilities. The flue gases are cleaned before leaving the plant, in order to meet the demands of Singapore's clean air restrictions. The heat generated is used to generate electricity. [7]

In 2007 the four incineration plants in Singapore incinerated 2.38 million tons of waste. At the moment the incineration plants are able to take care of all the waste but the disposed waste increases for every year. From 1970 to 2000, the amount of solid waste disposed of increased six times to 7600 tons per day. Continuing at this rate Singapore has to build a new incineration plant every 5-7 years.[8] The incineration plants also generate a large amount of ash that is disposed at Semakau landfill everyday. Everyday 1400 tons of ash and 600 tons of incinerable waste are disposed at the landfill.[9]. Continuing like this Singapore will need a new land fill of the same size as Semakau every 25-30 years.[10] For land-scarce Singapore this is not sustainable in the long run.

[7] NEA (2002), brochures on incineration plants
[8] MEWR (2008), Chapter 4
[9] NEA (2002), brochure on Semakau landfill
[10] MEWR (2008), Chapter 4

2.2 Biogas production and use

The production of biogas by anaerobic digestion is a natural process which occurs in nature where there is no available oxygen. That could be in the sediments of a lake, in a swamp, in the stomach of a cow or when organic waste is land filled. The fact that the decomposition of organic material could produce gas was first described in the end of the 17th century, but that the gas was produced by microorganisms was not proved until about 200 years later. When the details of the process were more known of, attempts were made to make use of the anaerobic digestion process. In the end of the 19th century the first practical digesters were built to treat sewage sludge and that has been a common use of the anaerobic digestion until present day. Later on, the use of anaerobic treatment has widened to a variety of different substrates, such as waste water, agricultural waste, manure, organic municipal waste, and all sorts of organic industrial waste.[11]

2.2.1 The process

Biogas is formed when organic matter is digested in the absence of oxygen; this process is called anaerobic digestion. The digestion is made by enzymes and bacteria during the below described four main steps.[12,13] The process is also described in figure 2.

- Hydrolysis – In this step the organic polymers are broken down by enzymes which are emitted when fermentative bacteria attach to the molecules in the waste. Proteins are broken down to amino acids, carbohydrates to sugars and lipids to fatty acids. The carbohydrates take a few hours to break down and the fats a few days. Lignocellulose and lignin are only hydrolyzed to a limit extent. The residue from the anaerobic digestion contains about 40-50% of lignin and 40-50% of cellulose and hemicellulose.

- Acidiogenesis – During this step the molecules from the previous step is broken down further by bacteria, without the help from enzymes. The main products from acidification are short chained fatty acids, alcohols, carbon dioxide gas and hydrogen gas. The carbon dioxide and hydrogen gas can be converted into methane directly by methanogenic bacteria.

- Acetogenesis – In this step the fatty acids and the alcohols are broken down to smaller components, mainly carbon dioxide, acetate and

[11] Braun (2007)
[12] Pesta (2006)
[13] Deublein & Steinhauser (2008)

hydrogen gas. During acetogenesis hydrogen and carbon dioxide are reduced to acetic acid; this is made by homoacetogenic microorganisms. The acetogenic bacteria produces H_2, but the break down of long-chain fatty acids to acetate can only take place during a very low hydrogen partial pressure. This means that the acetogenic bacteria must live in symbiosis with methanogenic bacteria which need hydrogen for their survival.

- Methanogenesis – This is the last step in the process, where different methanogenic bacteria convert carbon dioxide, hydrogen gas and acetate into methane. These bacteria can not operate in the presence of oxygen.

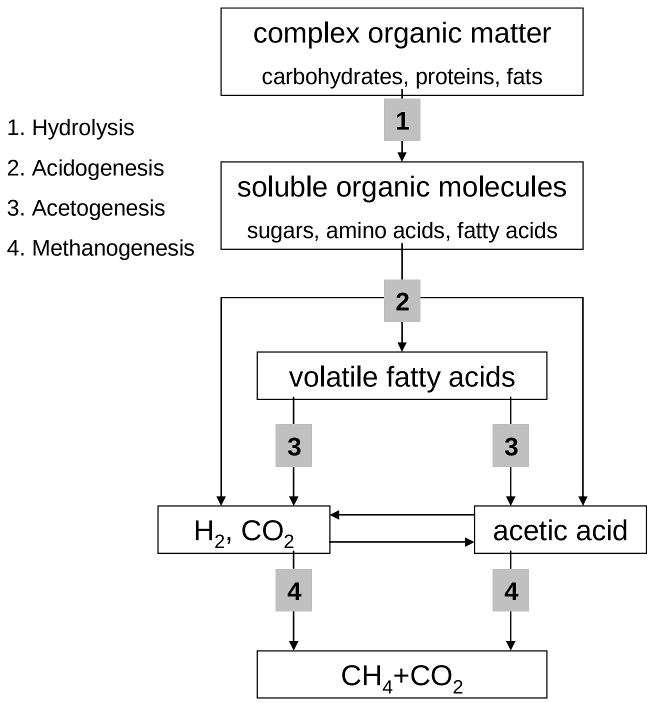

Figure 1: The biogas process[14]

The produced biogas consists mainly of methane and carbon dioxide. The composition varies between different substrates and technologies. Usually the gas from anaerobic digestion of food wastes consists of 70 %–80 % methane, by volume[15], while the rest is carbon dioxide. Traces of other

[14] Based on Angenent & Wrenn (2008)
[15] Harikishan (2008)

substances can be found in the gas such as water, hydrogen sulfide, siloxanes and particles.[16]

Methane is the energy carrier in biogas and therefore the so called methane yield is used to quantify how well a biogas process is working. The methane yield depends on several factors, but the substrate composition is probably the most important. Sometimes the term biogas yield is used, and it usually refers to the amount of gas (CH_4 and CO_2) that is produced from the substrate. In table 1 the biogas yields for the main components in organic waste are listed.

Table 1: Biogas yield for different components in organic waste[17]

	Gas yield L/kg	CH_4 % by volume	CO_2 % by volume
Carbohydrates	747	50	50
Lipids	1250	68	32
Proteins	700	71	29

The amount of crude fat in source sorted municipal organic waste was in a Swedish study determined to 4.1% and crude protein to 12.5 % of the wet weight. [18] The waste had a dry matter content of 30.8%. In another study the amount of carbohydrates in food waste was 37.8% of the dry weight[19], which is 11.6% of the wet weight if the dry matter content is 30.8%.

2.2.2 Process Parameters

There are several parameters that affect the biogas process; four of the most important are listed in table 2.

Table 2: Important parameters in the biogas process[20]

Parameter	Hydrolysis/ Acidogenesis	Methanogenisis
Temperature	25-35	Mesophilic:32-42 Thermophilic: 50-58
pH value	5.2-6.3	6.7-7.5
Required C:N:P:S	500:15:5:3	600:15:5:3
DM content	<40%	<30%

[16] Harikishan (2008)
[17] Braun (2007)
[18] Nordberg & Edström (1997)
[19] Shin et al. (2004)
[20] Deublein & Steinhauser (2008)

2.2.2.1 Temperature

There are two main temperatures where anaerobic digestion is usually performed. These are the mesophilic interval which is in the range 35 ºC -40 ºC and the thermophilic of about 55 ºC. The reason for this is that the methanogenic organisms are most effective at these temperatures. It is very important to keep the temperature constant in a biogas reactor to keep the process working well, because the methanogenic bacteria are very sensitive to sudden changes in temperature. Especially for the thermophilic organisms it is important that the temperature does not fall below 45 ºC, or these bacteria will be killed.[21]

The fact that the mesophilic bacteria are less sensitive to temperature changes is one of the reasons why it is often preferred to perform the AD in this temperature range.[22] Another positive thing is that the need for heating is lower in the mesophilic process, which is very important in cold climates. In warmer climates such as in Singapore, the heat can be taken from waste heat if the biogas is used to produce energy, but in colder climates where the heat is sold as well as the electricity, a great need for heating in the plant will lead to a default of income.

There are several good arguments to use the thermophilic process despite the high sensitivity to temperature change. In the thermophilic process the degradation of the ingoing material is about 50 % higher than for the mesophilic process.[23] This means that the reactor can be half as big as in the mesophilic case and still treat the same amount of substrate. When a temperature exceeding 55 ºC is used, all eventual germs in the substrate is killed, which is not the case for the mesophilic process where an extra hygienic step might be needed.[24]

2.2.2.2 pH-value

Methanogenic bacteria are very sensitive to changes in pH-value. When carbohydrates are acidified there is no production of pH-buffering ions, as there is when proteins are acidified. Carbohydrates are also more easily acidified than proteins. If the pH-value starts to decrease and reaches a level lower than 6.5 there will be a further decrease of the pH-value by the hydrolytic bacteria and this might lead to a complete stop of the methanisation.[25]

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[21] Wilkie (2008)
[22] Wilkie (2008
[23] Deublein & Steinhauser (2008)
[24] Pesta (2006)
[25] Khanal (2008)

When having a well balanced biogas process the pH range remains buffered in the range 7.2 to 8.2.[26] There are two buffering systems that guarantee that the pH-value will stay in a neutral range. First there is the carbon dioxide/hydrogen carbonate/carbonate buffer system. This system regulates the pH-value by dissolving CO_2 in the water. If the pH-value is to low, more CO_2 will dissolve as uncharged molecules in the substrate. If the pH-value is too high the CO_2 in the substrate will form carbonic acid, which is then split into ions, and will increase the concentration of hydrogen ions, see equation 1.[27]

Equation 1

$$CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + 2CO_3^{2-}$$

The other buffer system is called ammonia-ammonium buffer system. If the pH-value in the substrate is too low, ammonium ions will be produced and during this hydroxyl ions will be released. If the pH-value gets to high there will be an increased formation of free ammonia molecules, see equation 2.[28]

Equation 2

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$$
$$NH_3 + H^+ \leftrightarrow NH_4^+$$

The buffering systems can be overloaded by e.g. feeding of acid waste, toxic substances, decrease in temperature or feeding of too much waste into the reactor.[29]

2.2.2.3 Required C:N:P:S

Since the production of biomass is very low in the anaerobic process, there is no great need for nutrients, as can be seen in table 2. If there is too much nitrogen in the substrate there will be an increased production of ammonium which will slow down the methane production. If there is a lack of nitrogen it means that the microorganisms will not get sufficient supply of nitrogen and can not grow, thus the methane production will decrease. Therefore it is very important to have the right C:N ratio.[30]

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[26] Deublein & Steinhauser (2008)
[27] Deublein & Steinhauser (2008)
[28] Deublein & Steinhauser (2008)
[29] Deublein & Steinhauser (2008)
[30] Braun (2007)

2.2.3 Different use of biogas

Biogas can be used for different purposes depending on the demand. Most commonly the gas is used in a plant to generate electricity and heat. An alternative to this is to upgrade the gas to the standards of natural gas, so that it can be injected into a natural gas grid or used as a vehicle fuel. Upgraded biogas can be used in any appliance that has been constructed for compressed natural gas.[31]

When upgrading the biogas the CO_2 has to be removed in order to increase the percentage of the methane content. This can be made by several different technologies, but scrubbing with water is the most common. The technique uses the fact that CO_2 can easily solve in water while the hydrocarbons are hydrophobic. When cleaning the biogas, the gas flows through a column with pressurized warm water and the CO_2 is transferred to the water. When the gas leaves the column the methane rate is higher than 95%. The scrubbing process also removes traces of H_2S and other impurities.[32,33]

[31] Wilkie (2008)
[32] Deublein & Steinhauser (2008)
[33] Linné & Dahl (2001)

2.3 Biogas from the organic fraction of municipal solid waste

There have been a number of articles written on the subject of treatment of organic waste the last years, some of them analyzing the option to produce biogas from the organic fraction of municipal solid waste (OFMSW) by anaerobic digestion (AD). But one has to be careful before applying the result on the Singapore situation. In a study from Thailand, incineration and AD was compared for municipal waste. In the incineration scenario all municipal waste was incinerated and in the other scenario the organic fraction was used to produce biogas trough AD and the non-organic fraction was land filled. The results from the study show that the option with AD was to prefer to incineration in terms of GWP.[34] However, this is mainly due to the large content of organic waste in the waste stream in Thailand. Of the municipal waste more than 60% is biodegradable and this is causing problems with incineration due to the high moisture content in the waste.[35] In Singapore only about 37% of the domestic waste is organic and only 24% of the waste incinerated.[36] This means that the study can not be used to prove that AD is a suitable waste management option in Singapore but parts of the results can be used to make an assessment of the possibilities in Singapore.

To find studies that can be applied in the Singapore context; one has to look in countries with similar waste streams like Singapore. In many of the studies made in European countries, Canada or USA the organic fraction is, or is assumed to be, around 30% of the municipal waste, therefore studies from these countries are preferable to those from countries like Malaysia, Thailand or Indonesia.

Several articles, analyzing the environmental impacts of AD and comparing with e.g. incineration, have been published the last years. During 2006 and 2007 Berglund and Pålsson published three articles about the energy use and emissions from biogas production. The papers analyze the energy performance and the emissions from the whole process chain, from collecting or harvesting of the material used for biogas production to the end use of the biogas and the end use of the residue as fertilizer. Several different substrates are compared as well as different scales of the plants.

The first article deals with the energy balance of the systems, this study shows that the energy input is somewhere between 20 and 40% of the

[34] Chaya (2006)
[35] Chaya (2006)
[36] MEWR (2007), solid waste management.

energy content of the biogas produced.[37]. The variations can be caused by differences between the substrates, differences in design of the systems, and by allocations made in the study. Raw materials that need a lot of treatment before the AD process, such as OFMSW causes a significant increase to the energy input. The energy needed only at the biogas plant when treating OFMSW is 6-17% of the energy content of the biogas produced for heat and an additional 8-24% for electricity. For the recovery of the material 25% of the energy content in the biogas is used.[38] This study is based on a report by the same authors from 2003, the report analyzes the energy inputs in the different processes in the biogas systems very thoroughly, according to this report the energy input to the whole biogas system treating OFMSW is 20-60% depending on what data is used, the different data alternatives can all be found in the report.[39]

The second and the third article by these authors both describe environmental impacts. The first one analyzes the fuel-cycle emissions and the second one the impacts that occur when biogas production replaces different reference systems. Since the amount of emissions is partly based on the energy use, some of the results are similar to the ones from the energy assessment. For example, the pre treatment of the raw materials causes a significant amount of emissions, as well as collection of the OFMSW. Since methane leakage would contribute a lot to GWP, the authors point out that it is important to study the specific plant to get more reliable data on fuel-cycle emissions.[40]

The environmental improvements that biogas can lead to are often due to indirect effects. That is the general conclusion from the last article. The results show that replacing incineration of organic waste with AD in some cases may increase the level of emitted GHG.[41]

In a Danish study from 2003, similar results are described. Three different alternatives for handling of municipal waste are compared in terms of emissions. In the first scenario all the waste is incinerated, in the second one the organic fraction is sorted out and transported to a biogas plant and in the third one the organic fraction is transported to a composting facility. The results show that incineration has the least impact on the environment followed by AD and then composting.[42] This study focus mostly on

[37] Berglund & Börjesson (2006)
[38] Berglund & Börjesson (2006)
[39] Berglund & Börjesson (2003)
[40] Börjesson & Berglund (2006)
[41] Börjesson & Berglund (2007)
[42] Baky & Eriksson (2003)

acidification and eutrophication, in means of GWP the AD alternative is not worse than incineration according to the study.

In an Italian study from 2008 different scenarios for the handling of urban waste in Rome is compared. One of the scenarios includes AD of the organic waste and recycling of ferrous materials and other recyclables. The rest of the waste is incinerated. The biogas is upgraded and used together with natural gas. The residues from the AD process are dried and incinerated to produce power. The result shows that this scenario is preferable to incineration of all the waste.[43] The result is partly from the fact that it is unsustainable for Rome to incinerate all waste if there is no way to recycle all the ash, but also because the scenario including AD and recycling produces more electricity. The AD and recycling scenario can supply Rome with 15.47% of its energy demand compared to 13.44% for the incineration scenario.[44]

In a case study made in Sweden 2008, the result shows that it is better to treat organic waste by AD than to incinerate it.[45] Important processes that are included in the study are transport of the waste, processes at the biogas plant and the incineration plant respectively and upgrading of the gas to vehicle fuel. Indirect impacts that are included in the study are the use of biogas in vehicles instead of fossil fuels and the fact that less inorganic fertilizer has to be produced. Incineration had higher impact on GWP, acidification and eutrophication in this study. The total emissions of CO_2 from the biogas system are 286 kg/ton dry matter compared to 346 kg/ton dry matter from the incineration scenario.[46]

Another study that has similar results is a study from 2000. Three alternative ways of treating organic waste are compared; incineration with heat recovery, composting and anaerobic digestion. The OFMSW is co-digested with organic waste from industries, sewage sludge and manure from farms nearby. The non-organic fraction is incinerated. The produced biogas is upgraded and used as fuel in buses. The alternative including AD of the organic waste has the lowest GWP as well as acidification and eutrophication.[47] In this study indirect impacts are included, such as decreased use of fossil fuel due to the use of biogas in buses.

A pattern in these different studies seems to be that AD might not always be sustainable in combination with incineration of all the remaining waste. In

[43] Cherubini et al. (2008)
[44] Cherubini et al. (2008)
[45] Ljungkvist (2008)
[46] Ljungkvist (2008)
[47] Sonesson et al. (2000)

integrated systems where just a small amount is incinerated, and the different fractions are recycled AD seems to be a good option. When an alternative with AD of 50% of the organic fraction and incineration of the rest of the waste was compared to incineration of all waste, the AD alternative had a higher environmental impact.[48] On the contrary, an option where as much as possible is recycled, and the organic fraction is treated with AD and only the non-recyclable waste is incinerated is the option with the least environmental impact.[49]

Assuming that more and more of the recyclable waste, such as glass, metals, plastics and paper are recycled in Singapore, the organic fraction of the incinerated waste becomes a bigger and bigger part. When incinerating waste with low dry matter content, fossil fuels must be used to help combust the waste. This is the case in Thailand where the moisture content of the waste incinerated is 40-60%.[50] Since Singapore is striving towards increased recycling rates, AD might be a good option for treatment of organic waste.

That Singapore is in need of higher recycling rates is one of the conclusions from Tan and Khoo (2006). This study analyzes four different methods for waste managing that to some extent already exist in Singapore. These are incineration, land filling, recycling and composting. According to the study "the energy gained from the incineration of waste materials is outweighed by the air pollution generated from the incinerators". The intended pollutions are mainly heavy metals and dioxins/furans.

Different papers have presented very different conclusions regarding what the best way to treat OFMSW is. These differences seem to originate from the different system boundaries in the studies. One important factor is that in some studies, the energy supply to the biogas system is taken from the grid, not from the biogas plant itself, this is usually because the biogas is used as a vehicle fuel instead of for power generation. The emissions will of course be much higher if the electricity comes from fossil fuels instead of biogas. For example the electricity supply comes from natural gas in Berglund and Pålsson (2005), Börjesson and Pålsson (2006) and Börjesson and Pålsson (2007). In Baky (2003) the electricity comes partly from coal.

There are no articles written about the feasibility of using AD for treatment of OFMSW in Singapore and that is why the aim of my project is to do an analysis of the possibilities of using AD to treat the OFMSW in Singapore, and to point out in which areas further studies should be done.

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[48] Zhao et al (2008)
[49] Zhao et al (2008)
[50] Chaya (2006)

3 Methodology and system description

3.1 Functional unit

In order to make it possible to compare the environmental impacts from different products or processes LCA methodology uses a functional unit. The functional unit defines the function of the studied system and it is important to choose the functional unit so that the different alternatives can be compared in a fair way. If it is not possible to come up with a functional unit, the systems differ too much. If the systems do not have the same essential properties or functions they should not be compared using LCA.

Since the goal of this project is to study and compare alternative ways to take care of the OFMSW, the functional unit is 1 ton of OFMSW. In order to take in account indirect 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 why 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.

3.2 Life cycle assessment

In this study LCA methodology was used. In figure 1 the different stages of LCA is shown. First of all the goal and scope of the study should be defined. The system boundaries must be clearly stated, since they might have a big impact on the result of the study. When the goal and scope are defined the inventory analysis can start. This is where data about all the processes are gathered; these data can be presented in a report, and is then called LCI (life cycle inventory). However, in LCA the data from the inventory analysis is further processed in the impact assessment, where the different data is sorted into different categories depending on what environmental impact they have. These categories can be for example, global warming potential, acidification, eutrophication etc. Through the impact assessment the total environmental impact of the studied system can be more clearly evaluated. Sometimes a fourth step is included in LCA, called weighing. Weighing is a subjective method where the data is aggregated even more. The different environmental impacts are weighed against each other based on e.g. political goals, economical goals or the critical load of different substances. [51,52] In this study no weighing has been performed.

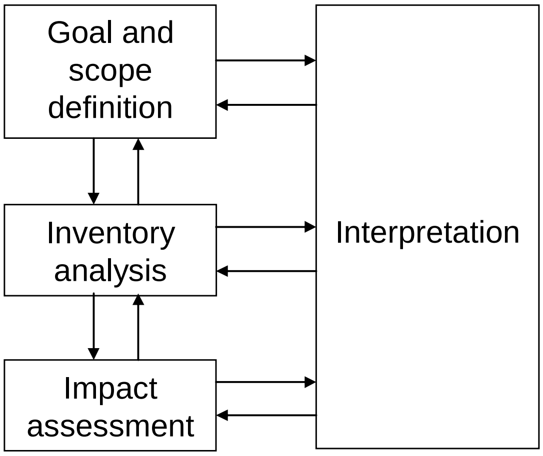

Figure 2: The basic stages of LCA[53]

3.3 Assessment method

This study was made at Singapore Institute of Manufacturing Technology in Singapore. It would have been possible to perform this study in Sweden, but being in Singapore has made it possible to more easily find information about the Singapore waste management system, to contact people in NEA and other agencies and to meet with people with experience of performing LCA in Singapore.

As can be seen in figure 2 LCA is not a linear process, which means that one usually is working with several stages at the same time. The goal and scope for this study was redefined several times in the beginning of the study. At first the systems did not include indirect environmental impacts such as decreased emissions due to replacing fossil fuels. But during literature studies and especially studies of LCA papers, it seemed fairer to include the indirect impacts because that is the common practice and it makes the efficiency of the systems visible. In the initial stage of the study only GWP was considered, but during collection of data on GHG-emissions data on other emissions was found as well. This made it easy to include also acidification and eutrophication.

Because this study is mainly based on data from literature, such as academic papers, governmental reports, books etc. this study was preceded by a quite

[51] Rydh et al. (2002)
[52] ISO 14010 (2006)
[53] ISO 14010 (2006)

extensive literature study, which is partly reported in chapter 2. Data on energy use and emissions from different processes was recovered from literature and contacts at the national environment agency (NEA) in Singapore and at biogas plants in Sweden. This data was used to model the different scenarios using Excel. There are several software products that are specialized to help perform LCA but Excel was used since the time of this project was limited to about 20 weeks and learning a new soft-ware would have been too time consuming.

All the data was recalculated to units per ton of OFMSW, since 1 ton of OFMSW is the functional unit. The emissions from every process were then aggregated using characterization factors to be able see the environmental impact from every process. The characterization factors used can be found in appendix 4. After this some sensitivity analysis was performed in the areas where changes were considered to be able to affect the end results in particular.

3.4 Scope definition

3.4.1 Presentation of the scenarios

There are four scenarios that are being compared in the study. The reference scenario is mainly based on data on how the current waste management system in Singapore is working.[54,55,56,57] The biogas scenarios are models which are not based on any real biogas plants in specific. They are all producing electricity because Singapore is in great need of domestically produced electricity, since almost all the electricity in Singapore comes from imported natural gas and oil. 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, and since the mean temperature in Singapore is so high that the heat needed for heating the substrate is still not that high, even with a thermophilic process.

In this study I have assumed the digestate to be dewatered and composted after the digestion step. This is mainly because there is almost no need for fertilizer in Singapore, which means that the digestate has to be transported to e.g. Malaysia. By dewatering and composting the transport of the compost material that is not used in Singapore is more profitable since it has a higher dry matter content. By composting the digestate it is further decomposed, this also reduces the overall volume of the material. A just as

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[54] NEA & MEWR (2006), Integrated solid waste management in Singapore
[55] NEA (2002), Brochures on incineration plants and Semakau landfill
[56] Tan & Khoo (2006)
[57] NEA, Solid waste collection system

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 to the bio reactor, the use of fresh water will be as low as possible.

Below is a short description of the different scenarios:

- *Reference Scenario* - describes the current management of OFMSW in Singapore. The waste is transported from the citizen or facility to one of the four existing incineration plants where it is incinerated. From the incineration plant the ash is transported to Tuas marine transfer station where it is loaded on barges. Once a day the ash is transported by barge to Semakau landfill which is situated on Semakau island about 25 km from the transfer station.

- *Scenario Large* – the OFMSW is transported to a large scale biogas plant where it is processed. The produced biogas is used to generate electricity. The byproduct from the digestion is composted and the compost is sold as soil improver.

- *Scenario Medium* – the OFMSW is transported to several mid scale biogas plants where it is processed. The produced biogas is used to generate electricity. The byproduct from the digestion is composted and the compost is sold as soil improver.

- *Scenario Small* – the OFMSW is directly disposed into a small scale biogas plant. The produced biogas is used to generate electricity. The byproduct from the digestion is composted and the compost is sold as soil improver. These plants can for example take care of food waste from a food centre or a shopping centre, they are not meant to take care of all the OFMSW in Singapore.

3.4.2 System boundaries

The system boundaries are very important in LCA and they can have a major impact on the results. In this section the system boundaries for the different scenarios are presented and motivated.

3.4.2.1 *Waste properties*

The OFMSW is sorted out by the disposer, and picked up by trucks at the house or facility. When the waste is separated from the plastic bags at the plant some of the waste might cling on to the bag, this is not taken into account in this study. Since this happens in all the scenarios, there is no problem canceling out the effects from this. In this study dry matter content of the OFMSW was assumed to 30%.[58,59,60]

3.4.2.2 *Reference scenario*

The material flow of the reference scenario is shown in figure 3, and all the processes that are included and not included in the reference scenario appears in table 3. Methane leakage from the landfill is not included in the study because it has been shown that the leakage of methane from Semakau landfill is minimal[61], this is because the ashes contains almost no organic compounds. 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.

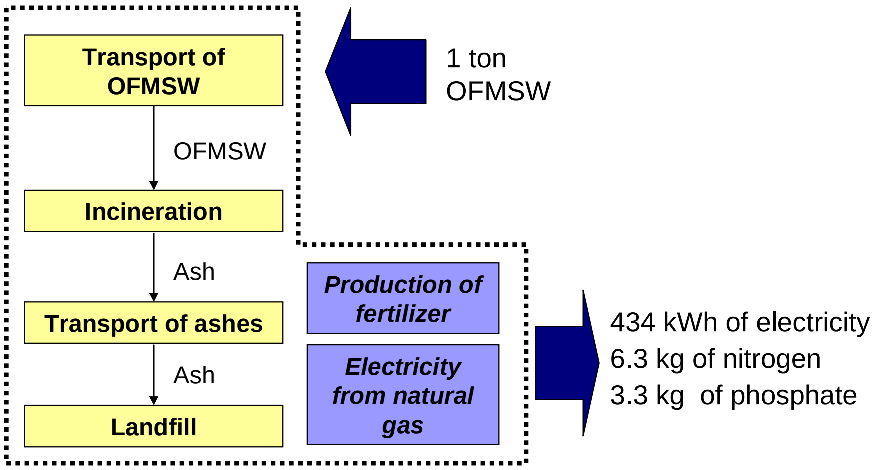

Figure 3: Material flow of the reference scenario

[58] Zhang et al (2006)
[59] Börjesson & Berglund (2006)
[60] Wong et al. (2008)
[61] Tan & Khoo (2006)

Table 3: System boundaries for the reference scenario

Included processes	Not included processes
– *Transport of waste to incineration plant* – *Incineration* – *Electricity used at the incineration plant* – *Oil used to start up combustion* – *Transport of ash to landfill* – *Production of fertilizer* – *Electricity from natural gas*	– *Manufacturing of vehicles or machines used* – *Methane from landfill* – *Vehicles and machines used at the landfill site.* – *Production of diesel and fuel oil* – *Production of natural gas*

Assumptions made in the reference scenario:

- All heat and electricity needed in the incineration process is recovered from the plant.

3.4.2.3 Scenario Large

In figure 4 the material flow for scenario large is stated. The anaerobic digestion step includes several pre-treatments. The data on electricity use was found as one number for the whole plant, and does not tell how much electricity that is used in every treatment step.

The processes that are included and not included in the scenario appear in table 4. The waste water is led back into the bio reactor, why there is no reason to look into waste water treatment.

Table 4: System boundaries for scenario medium and large

Included processes	Not included processes
– *Transport of waste to bio-gas plant* – *Pre-treatment* – *Anaerobic digestion* – *Dewatering of residue* – *Composting* – *Transport of compost*	– *Manufacturing of vehicles or machines used* – *Treatment of waste water* – *Production of diesel* – *Spreading of soil improver* – *Possible emission of methane from soil improver when back in soil..*

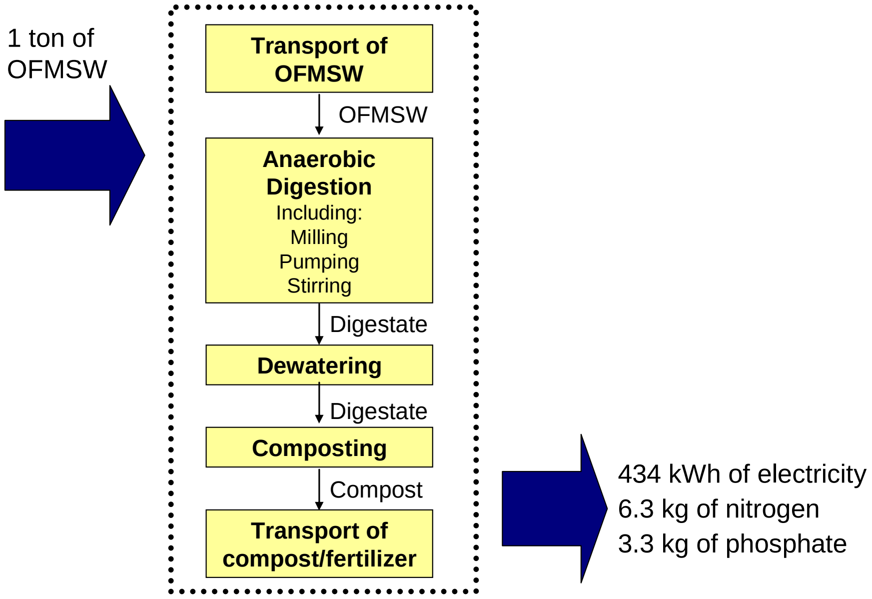

Figure 4 Material flow of scenario Large

3.4.2.4 Scenario Medium

In figure 5 the material flow of scenario medium is shown. The processes included are the same as for scenario large, see table 4. Electricity from natural has been added to the scenario since the scenario generates less electricity than scenario Large. The data on electricity at the biogas plant is also in this case on figure for the whole plant.

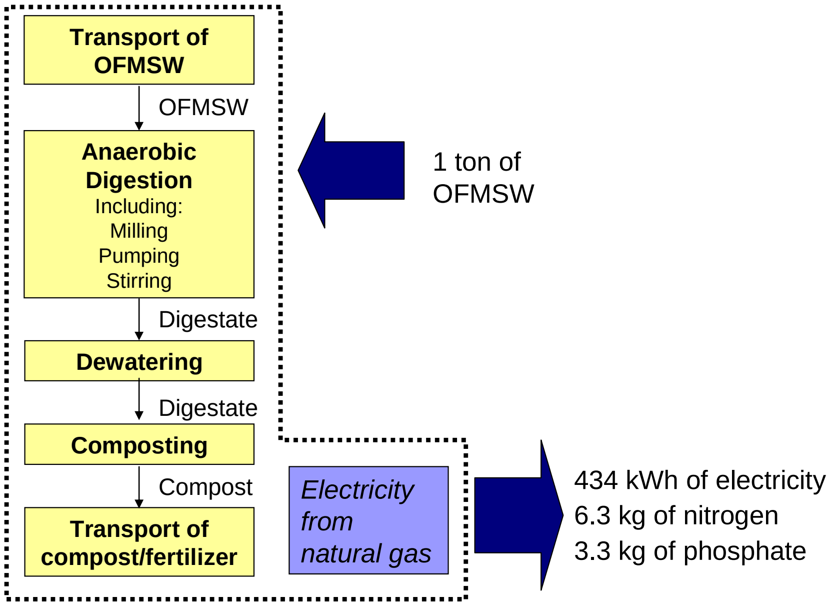

Figure 5 Material flow for scenario Medium

3.4.2.5 Scenario Small

In figure 6 the material flow of scenario small can be seen. The material flow is the same as in the other biogas scenarios, but there is no transport of the waste. To make the output from this scenario the same as for the other scenarios, electricity from natural gas has been added. The processes that are included and not included in scenario small appear in table 5.

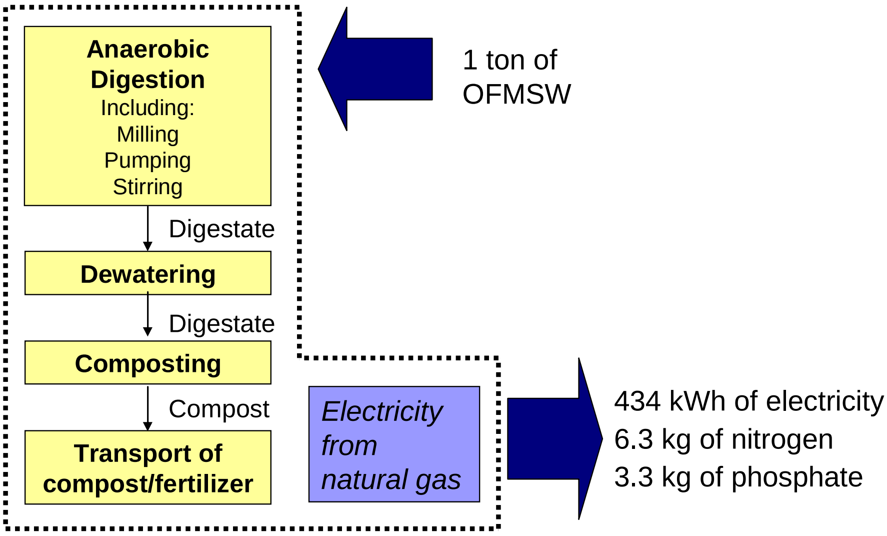

Figure 6 Material flow of scenario small

Table 5: System boundaries for scenario small

Included processes	Not included processes
– *Pre-treatment*	– *Manufacturing of vehicles or machines used*
– *Anaerobic digestion*	– *Treatment of waste water*
– *Dewatering of residue*	– *Production of diesel*
– *Composting*	– *Spreading of soil improver*
– *Transport of compost*	– *Possible emission of methane from soil improver when back in soil.*
– *Electricity from natural gas*	– *Production of natural gas*

3.4.2.6 Assumptions made in all the biogas scenarios

- At the biogas plants the waste is mixed with water to get a dry matter content of 10%
- The methane yield for the OFMSW is 0.40 m^3 CH_4/kg DM, see appendix 1.
- The biogas that is produced during composting is recovered, thus there is no emission of methane from the compost process.

- The leakage of biogas from the plant is assumed to be 1% of the produced biogas.[62]

- The same amount of heat that is needed for a mesophilic process in Sweden (south) is needed for the thermophilic process in Singapore. Based on that the temperature difference, see appendix 2.

- Heat and electricity needed in the processes are taken from the biogas plant.

- There is no sale of heat from the plants; the only heat recovered is the amount that is used at the plant.

- The produced biogas contains 70% CH_4 and 30% CO_2.[63]

- The efficiencies for the gas turbines are 40% for the medium scale scenario and 30% for the small scale scenario.

3.4.2.7 Transports

The emissions generated and the energy used during the transports has been calculated using a tool called NTM Calc.[64] NTM Calc is software that calculates emissions from transports based on type of vehicle, distance, type of fuel and the load. All transports are assumed to have an empty return transport. In NTM Calc the empty transport is added by dividing the average load by 2. For the collection routes there is no empty transport back, but the average load has been divided by 2 to compensate for the fact that the truck is empty when starting and filling during the route.

It is hard to make assumptions about the exact distances that the waste will be transported from the disposer to the plant. But the important thing is not the exact distance but the difference in distance between the different scenarios. The transport distance has been divided into two sections. First there is the collection, where the truck goes from house to house to pick up the waste, after that there is the transport of the waste to the plant The collection route has been assumed to be 9 km per collection truck for all scenarios (scenario small does not have any transport of waste). Information on how the collection route was estimated is found in appendix 5.

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[62] Börjesson & Berglund (2007)
[63] Ljungkvist (2008)
[64] NTM Calc (2003)

3.5 Data quality

This study is not a case study, which means there are no specific biogas plants where the data is taken from. The data is taken from several other studies, contacts at different plants, theoretical calculations and assumptions. In the reference scenario a lot of the data is taken from the actual incineration plants in Singapore, or from a study on waste management made in Singapore.[65]

When it comes to data about the biogas scenarios it has been taken from studies made mainly in Europe. This is because countries like Germany, Sweden and Denmark is leading in biogas and biogas research. This may in some cases lead to uncertainties, but it has been necessary because there is almost no data to get from Singapore, and many of the countries surrounding Singapore have very different waste streams from Singapore and are much less economically developed. Therefore, the data from Europe is often easier to apply to the Singapore context than data from e.g. Malaysia, Thailand or Indonesia.

For data on the properties of the organic waste and on waste management most of the data could be found through NEA (National Environment Agency) and MEWR (Ministry of the Environment and Water Resources) in Singapore

Since almost all data is taken from literature, this study can not be used to describe the properties of any biogas plant in particular, the study is meant only as a comparison between these different ways to treat OFMSW in Singapore.

[65] Tan & Khoo (2006)

4 Inventory

4.1 Reference scenario

4.1.1 Transport of waste

The collection and transport of waste in Singapore are provided by four waste management companies. Singapore is divided into 9 areas and in every area one of the four companies provides the collection and transport of municipal solid waste.[66] The waste is collected from residences and other facilities, such as food centers or shopping centers. After that the waste is transported to one of the four incineration plants. Naturally, there is no way to know the exact distance a collection truck is traveling to collect the waste and to get to an incineration plant. Therefore the distance for collection has been assumed to be the same as for the biogas scenarios, which is 9 km. The assumption of the distance to the incineration plants is based on the assumption for biogas scenario large. However, since there are four incineration plants, the distance has to be shorter. I have set the transport distance to 15 km. Details on how the transport distances were estimated can be found in appendix 5.

The energy use and emissions from collection and transport of the waste to an incineration plant can be seen in table 6.

Table 6: Emissions and energy use due to the transport from disposer to incineration plant[67]

Emissions		Unit
CO_2	3.6	kg/FU
NO_x	32	g/FU
HC	1.8	g/FU
CO	3.5	g/FU
SO_2	0.0046	g/FU
Energy use		
Diesel	13.9	kWh/FU

[66] NEA, Solid waste collection system
[67] NTM Calc (2003)

4.1.2 Incineration process

In 2007 there was 974 945 MWh of electric energy generated from incineration of waste in Singapore, 20 % of that energy was used at the plants while the rest was sold.[68] In table 7 the energy use is listed together with emissions from the combustion. The electricity use is calculated by taking 20% of the total amount of generated electricity in 2007 divided by the total amount of waste incinerated that year. The electricity generated from OFMSW was calculated by using the calorific value for food waste in Singapore, see appendix 7. No data on how much heat that is used at the plants was found. But since the used heat is a byproduct from the electricity generation, the heat does not add on to the emissions. In the emissions from combustion of the waste, emissions from the auxiliary oil burners needed for start up are included. Data on emissions from incineration of OFMSW is taken from Tan and Khoo (2006). Data on use of oil was given by NEA[69] and emissions from combustion of the oil are taken from Uppenberg et al. (2001).

Table 7: Energy use and emissions from combusting at the incineration plant

Electricity use	79.6	kWh/FU
Electricity from OFMSW	251	kWh/FU
Net electricity out-put	171	kWh/FU
Heat use	n.a.	kWh/FU
Heat generated	n.a.	kWh/FU
Land use[70]	10.1	FU/yr m3
CO_2 (fossil)	0.376	kg/FU
CO_2 (bio)	586	kg/FU
CH_4	2.48	mg/FU
N_2O	2.48	mg/FU
NO_x	376	mg/FU
CO	74.6	mg/FU
SO_2	891	mg/FU

4.1.3 Transport of ash

The four incineration plants in Singapore produce 1400 tons of ash every day. The ash is transported to Tuas marine transfer station (TMTS) by 35-ton trucks. After that the ash is transported by a barge to the off shore land fill on Semakau island.[71] The distance between the incineration plants and TMTS has been calculated by taking the distance from each plant to TMTS

[68] NEA (2002), Brochures on incineration plants
[69] e-mail correspondence with Wong Chak Huat, NEA
[70] NEA (2002), Brochures on incineration plants
[71] NEA (2002), Brochure on Semakau landfill

and then multiply it by the share of the total amount of ash that comes from the plant. The distance is then estimated to the sum of these four figures. This makes the calculated distance from the incineration plant to TMTS 11 km. The distance from TMTS to Semakau island is 25 km.

The emissions and the energy use of the transport of ash are listed in table 8-10.

Table 8: Emissions and energy use from transport of ash by truck[72]

Emissions		
CO_2	0.78	kg/ton ash
NO_x	7.0	g/ton ash
HC	0.40	g/ton ash
CO	0.77	g/ton ash
SO_2	0.001	g/ton ash
Energy use		
Diesel	3.06	kWh/ton ash

Table 9: Emissions and energy use from transport of ash by barge[73]

Emissions		
CO_2	1.1	kg/ton ash
NO_x	27	g/ton ash
HC	0.75	g/ton ash
CO	1.3	g/ton ash
SO_2	9	g/ton ash
Energy use		
Fuel oil	1.94	kWh/ton ash

Table 10: Total use of energy and emissions from transport of ash[74]

Emissions		
CO_2	0.32	kg/FU
NO_x	5.8	g/FU
HC	0.20	g/FU
CO	0.35	g/FU
SO_2	1.54	g/FU
Energy use		
Fuel	0.861	kWh/FU

[72] NTM Calc (2003)
[73] NTM Calc (2003)
[74] NTM Calc (2003)

4.1.4 Indirect impacts

Since the incineration scenario does not produce any fertilizer and generates less electricity than the large biogas plant (the most efficient plant), emissions from fertilizer production and electricity from natural gas has been added. In table 11 the emissions from production of fertilizer are listed No data on energy use during fertilizer production was found. In table 12 the emissions from the extra electricity from natural gas are listed.

Table 11: Emissions from production of fertilizer

Emissions[75]		
CO_2(fossil)	24.8	kg/FU
CO	8.81	g/FU
NO_x	76.0	g/FU
SO_2	85.6	g/FU
HC	6.74	g/FU
CH_4	29.9	g/FU

Table 12: Amount of electricity and emissions from combustion of natural gas

Emissions[76]		
CO_2(fossil)	130	kg/FU
CO	57	g/FU
NO_x	236	g/FU
SO_2	1.97	g/FU
HC	1.97	g/FU
CH_4	7.86	g/FU
Energy		
Electricity	257	kWh/FU

4.2 The biogas scenarios

4.2.1 Methane yield

There are no available data on the composition of the food waste in Singapore. This makes it impossible to calculate the expected methane yield from the waste. Data from several studies that are dealing with anaerobic digestion of OFMSW under thermophilic conditions were recovered. From this data an average methane yield of 0.4 m^3 CH_4/kg TS was calculated. This methane yield has been used to perform several calculations in the study. Details about what references the biogas yield is based on, and further explanation can be found in appendix 1.

[75] Börjesson & Berglund (2007)
[76] Börjesson & Berglund (2007)

4.2.2 Transport of waste

4.2.2.1 Scenario Large

The collection route is 9 km and the distance from the collection area to the plant has been estimated to 25 km, see appendix 5. The emissions caused by the transport of the waste and the energy used by the truck are listed in table 13.

Table 13: Emissions and energy use due to the transport from disposer to biogas plant[77]

Emissions		
CO_2	5.1	kg/FU
NO_x	46	g/FU
HC	2.1	g/FU
CO	5	g/FU
SO_2	0.0065	g/FU
Energy use		
Diesel	19.4	kWh/FU

4.2.2.2 Scenario medium

In this scenario the transport distance from the collection area to the plant is shorter than in the large scale scenario, due to the fact that there is a need for a larger number of plants to take care of all the OFMSW of Singapore. In the large scale scenario all the waste is transported to the same place but in this case there is a need for 27 plants, assumed to be evenly spread out over Singapore. This means that the area around every plant is 27 times smaller than in the large scenario. In this scenario the distance is estimated to 5 km, see appendix 5. The emissions caused by the transport of the waste and the energy used by the truck are listed in table 14.

Table 14: Emissions and energy use due to the transport from disposer to biogas plant[78]

Emissions		
CO_2	2.1	kg/FU
NO_x	19	g/FU
HC	1.1	g/FU
CO	2.1	g/FU
SO_2	0.0027	g/FU
Energy use		
Diesel	8.06	kWh/FU

[77] NTM Calc (2003)
[78] NTM Calc (2003)

4.2.3 Biogas process

4.2.3.1 Scenario Large

In table 15 the energy use and emissions from the large scale biogas plant can be seen. Since all the energy is supplied internally, there is no use of electricity from the grid. The emissions from the biogas process originate from the combustion of biogas and from leakage of biogas. The electricity is generated by burning the biogas in a gas turbine. In this scenario the turbine has the efficiency of $40\%_{el}$ and $45\%_{heat.}$ The emissions from the combustion are taken from Börjesson and Berglund (2003) with two exceptions. The emitted carbon dioxide has been calculated, assuming complete combustion of methane and that the carbon dioxide in the gas is emitted to the air. The calculations can be found in appendix 3. The data on emitted N_2O is taken from IPCC.[79]

Table 15 Energy use and emissions from the large scale biogas plant

Electricity use[80]	31.5	kWh/FU
Electricity generated	466	kWh/FU
Net electricity out-put	434	kWh/FU
Heat use[81]	88.9	kWh/FU
Heat generated	524	kWh/FU
Land use[82]	10.7	FU/yr m^3
CO_2 (fossil)	0	kg/FU
CO_2 (bio)	335	kg/FU
NO_x	210	g/FU
CO	21.4	g/FU
N_2O	0.168	g/FU
SO_x	7.13	g/FU
CH_4	14.3	g/FU
CH4 (leakage)	859	g/FU

[79] IPCC (2006)
[80] UNFCCC (2006)
[81] Berglund & Börjesson (2003)
[82] UNFCCC (2006)

4.2.3.2 Scenario Medium

The only thing that is different between the medium and large biogas plant is the electricity use, which is higher at the medium scale plant. The energy use at the medium scale plant can be seen in table 16 together with the emissions from the plant. The emissions from the biogas process originate from the combustion of biogas and from leakage of biogas. The electricity is generated by burning the biogas in a gas turbine. In this scenario the turbine has the efficiency of $40\%_{el}$ and $45\%_{heat.}$ The emissions from the combustion are taken from Börjesson and Berglund (2003) with two exceptions. The emitted carbon dioxide has been calculated, assuming complete combustion of methane and that the carbon dioxide in the gas is emitted to the air, see appendix 3. The data on emitted N_2O is taken from IPCC.[83]

Table 16: Energy use and emissions from the medium scale biogas plant

Electricity use[84]	42.5	kWh/FU
Electricity generated	466	kWh/FU
Net electricity out-put	423.5	kWh/FU
Heat use[85]	88.9	kWh/FU
Heat generated	524	kWh/FU
Land use[86]	2.10	FU/yr m^3
CO_2 (fossil)	0	kg/FU
CO_2 (bio)	335	kg/FU
NO_x	210	g/FU
CO	21.4	g/FU
N_2O	0.168	g/FU
SO_x	7.13	g/FU
CH_4	14.3	g/FU
CH_4 (leakage)	859	g/FU

[83] IPCC (2006)
[84] Berglund & Börjesson (2003)
[85] Berglund & Börjesson (2003)
[86] e-mail correspondence Carl-Magnus Pettersson, Svensk Växtkraft AB

4.2.3.3 *Scenario Small*

The outputs from the biogas plant in scenario small are listed in table 17. The electricity demand is supplied by the plant itself as well as the heat demand. The emissions originate from combustion of biogas and leakage of methane. The heat use in this scenario is higher than in scenario large.

The electricity is generated by a gas turbine; the efficiency of the turbine is $30\%_{el}$ and $50\%_{heat}$. The emission data is taken from Börjesson and Berglund (2003) with two exceptions. The CO_2 emissions is calculated, see appendix 3. The data on emitted N_2O is taken from IPCC.[87]

Table 17: Energy use and emissions from the small scale biogas plant

Electricity use[88]	23.8	kWh/FU
Electricity generated	349	kWh/FU
Net electricity out-put	326	kWh/FU
Heat use[89]	150	kWh/FU
Heat generated	582	kWh/FU
Land use[90]	0.08	FU/yr m^3
CO_2 (fossil)	0	kg/FU
CO_2 (bio)	335	kg/FU
NO_x	107	g/FU
CO	10.1	g/FU
N_2O	0.168	g/FU
SO_x	6.71	g/FU
CH_4	13.4	g/FU
CH_4 (leakage)	859	g/FU

[87] IPCC (2006)
[88] Berglund & Börjesson (2003)
[89] Berglund & Börjesson (2003)
[90] e-mail correspondence with Krister Andersson, Hagavik Biogas plant

4.2.4 Indirect impacts

4.2.4.1 Scenario Medium

In order to make the output from all the scenarios the same, some electricity from natural gas has to be added to scenario medium. The amount of electricity that has to be added and the emissions from combusting the natural gas are listed in table 18.

Table 18 Electricity amount and emissions from combustion of natural gas

Emissions[91]		
CO_2(fossil)	5.53	kg/FU
CO	2.43	g/FU
No_x	10.1	g/FU
SO_2	0.0838	g/FU
HC	0.0838	g/FU
CH_4	0.335	g/FU
Energy		
Electricity	11	kWh/FU

4.2.4.2 Scenario Small

Since scenario small generates less electricity than scenario large this has to be compensated by electricity from natural gas. The additional emissions due to this fact are listed in table 19.

Table 19: Electricity amount and emissions from combustion of natural gas

Emissions[92]		
CO_2(fossil)	54.9	kg/FU
CO	24.1	g/FU
NO_x	99.8	g/FU
SO_2	0.832	g/FU
HC	0.832	g/FU
CH_4	3.33	g/FU
Energy		
Electricity	109	kWh/FU

[91] Börjesson & Berglund (2007)
[92] Börjesson & Berglund (2007)

4.2.5 Composting process

I have not included any extra energy use for the composting step, but for the dewatering there is a need of 6 MJ electricity per ton digestate.[93] I assume that 1 ton of substrate mixture (10% DM) gives 1 ton of digestate, and then 1 ton of raw material gives 3 tons of digestate. This means that the electricity used for dewatering 1 ton of raw material is 18 MJ. The electricity for dewatering is taken from the biogas plant. The electricity use for dewatering is included in the total electricity use of the plants that can be seen in table 15-17.

When composting the digestate there might be some production of biogas. In all the scenarios this biogas is assumed to be collected, thus the compost process does not contribute to the GWP of the scenarios. The methane yield has not been increased due to the biogas produced during the composting since no data was found on how much gas is formed.

[93] Berglund & Börjesson (2003)

5 Impact assessment

In the impact assessment the different emissions from the inventory is categorized and aggregated so that the impact on GWP, acidification and eutrophication can be seen. In table 36 in Appendix 4 the compounds that are included in the impact assessment can be seen together with the characterization factors used in the assessment.

5.1 Energy use

5.1.1 Electricity

There are three types of energy included in this study, electricity, diesel and heat. The electricity demand at the plant is a very important parameter, since it determines how much of the generated electricity that can be sold. In figure 7 the net electricity out put from the different scenarios can be seen. From the diagram it is obvious that the incineration plant is the least efficient of the four plants.

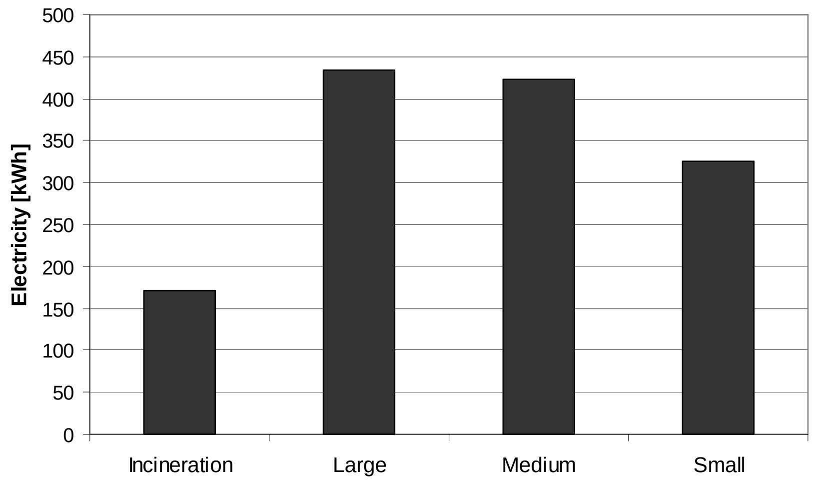

Figure 7 Net electricity out put from the different scenarios

In figure 8 the electricity demand at the plants is shown along with the generated electricity. Biogas scenario large and medium generates the largest amount of electricity and also has the highest output of electricity that can be sold. The incineration scenario has the highest electricity demand and the lowest net electricity output. This is because of the low efficiency when incinerating OFMSW. Electricity is used in the production of fertilizer, but no data on how much electricity that is used was found during research. Because of this the electricity use includes only the plants in the different scenarios.

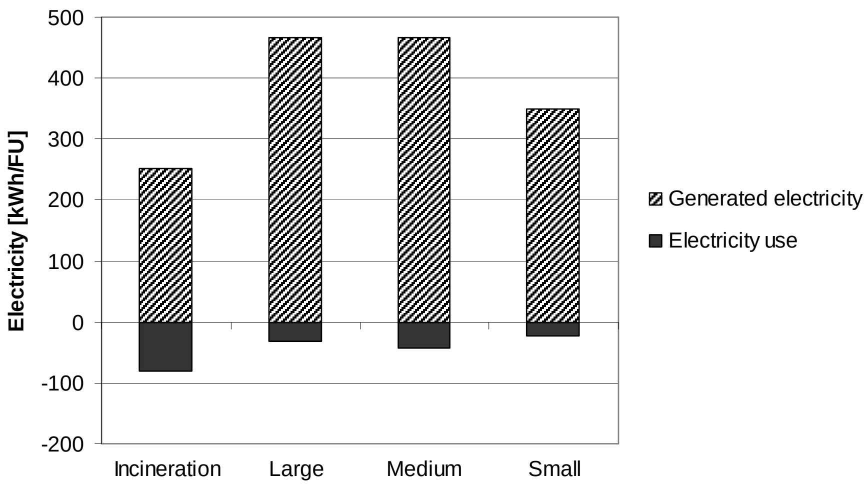

Figure 8: Electricity use and electricity generated at the different plants

5.1.2 Diesel

The use of diesel should be minimized since it results in a large amount of emissions. The diesel use of the scenarios is shown in figure 9. The diesel consumption is proportional to the total transport distance, which is why the diesel consumption is highest in the large scenario. The transport of compost contributes a lot to the use of diesel in the biogas scenarios. If the soil improver could be used in Singapore both the small scale and the medium scale scenario would use less diesel than the incineration scenario.

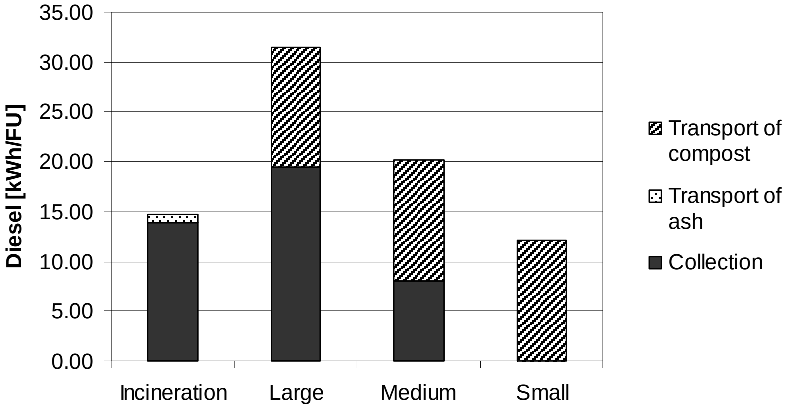

Figure 9: Diesel use in the different scenarios

5.1.3 Heat

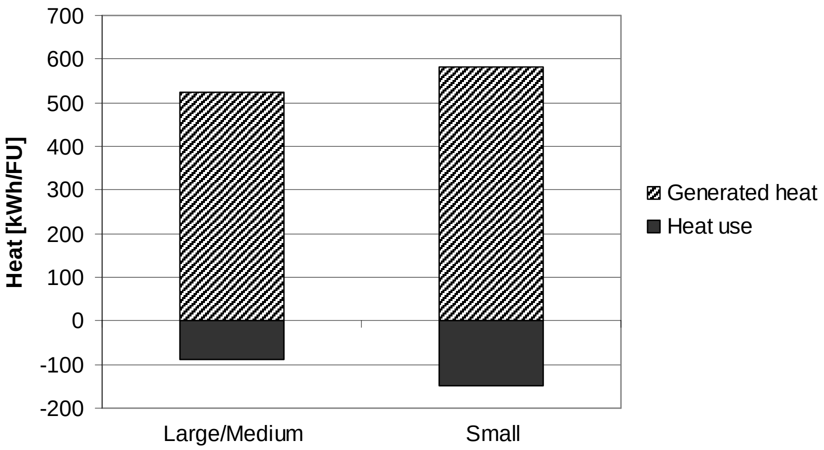

Figure 10: Heat use and generated heat at the different plants

When it comes to the use of heat, the most important thing in these scenarios is that the heat demand is smaller than the amount of waste heat that is generated from electricity generation. If there was a possibility to distribute and sell heat in Singapore, then the importance of keeping the heat demand as low as possible would be much greater. The heat demand and the generated heat are shown in figure 10. The incineration scenario is not included, since no data was found on heat use in incineration plants in Singapore.

5.2 Global warming potential

In this study only the fossil CO_2 are included in the impact assessment, this is because of the common practice not to include biogenic CO_2 when doing LCA. In figure 11 the total GWP from the studied scenarios can be seen, excluding the biogenic CO_2. Incineration has the highest GWP, followed by scenario small. This is mainly because of the low efficiency of these two systems, when generating electricity. As can be seen in figure 11, most of the GHG in these two scenarios comes from electricity from natural gas. In scenario large and medium the plant contributes with the largest amount of GHG. This is because of the methane leakage at the plants; since methane is a 21 times stronger GHG than carbon dioxide this has a big impact, even though the leakage is only 1% of the produced methane.

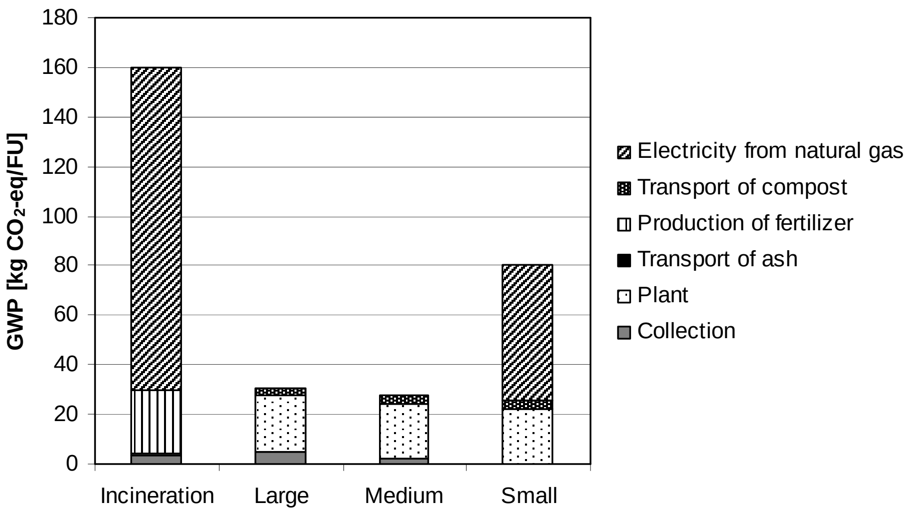

Figure 11: GWP from fossil CO_2 and other GHG

5.3 Acidification

Also for acidification the incineration scenario has the greatest impact, see figure 12. The biggest contribution comes from production of fertilizer and from electricity from natural gas. This is because the production of fertilizer causes large amounts of both SO_x and NO_x and the combustion of natural gas gives large amounts of emitted NO_x. In the biogas scenarios the plant causes a lot of acidification, this is mainly because combustion of biogas generates quite high emissions of NO_x. The small scale scenario has a lower impact on acidification than the other biogas scenarios because the micro biogas turbine causes less emissions of NO_x than the large turbine and because there is no diesel used for collection of the waste.

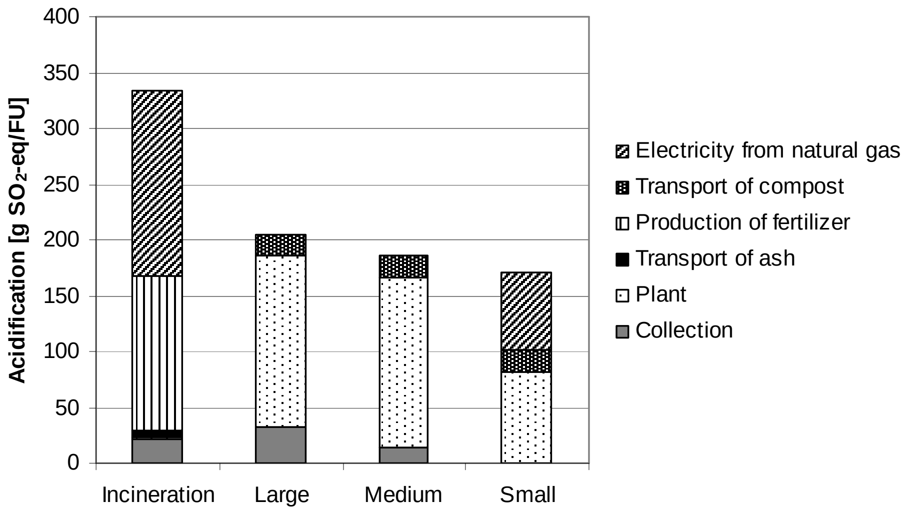

Figure 12: Acidification from the scenarios

5.4 Eutrophication

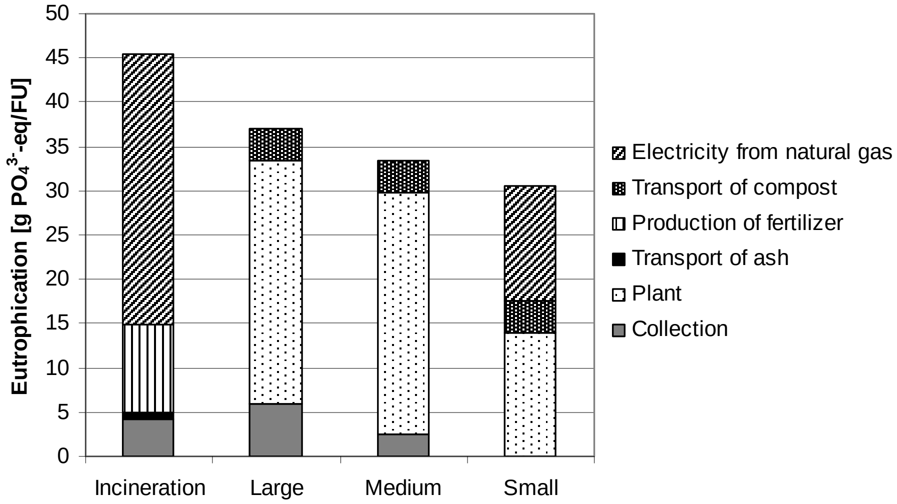

Figure 13: Eutrophication from the scenarios

For eutrophication the difference between the biogas scenarios and incineration is smaller than for both GWP and acidification, see figure 13. This is because the quite high emissions of NO_x from the combustion of biogas. The small scale scenario has a lower impact on eutrophication than the other biogas scenarios because the micro biogas turbine causes less emissions of NO_x than the large turbine and also because there is no collection and transport of the waste.

5.5 Land use

Land use is very important in Singapore since the country has such limited land area. According to data given by two biogas plants in Sweden, one medium scale plant and one small scale plant, they both use 1 ha of land for their plants. This makes the small scale plant very inefficient compared to the medium scale plant. The fact that the data is taken from Sweden means very high uncertainty in this case, since Sweden does not have any lack of land, and has a very low population density. In Sweden there is no need to try to use as little land as possible. However, the data on land use for the large scale biogas plant are taken from a Clean Development Mechanism (CDM) project design document for a large scale biogas plant in Singapore.[94] This data shows that the large scale biogas plant and the incineration plant use about the same amount of land area.

[94] UNFCCC (2006)

6 Sensitivity analysis

6.1 Methane leakage

Due to the fact that methane has such big impact on the GWP, even quite small amounts that are emitted from the biogas plants can cause a great difference in the results of this study. The methane leakage from the plants was to 1% of the produced gas, but with insufficient control of the leakage it might reach higher levels.

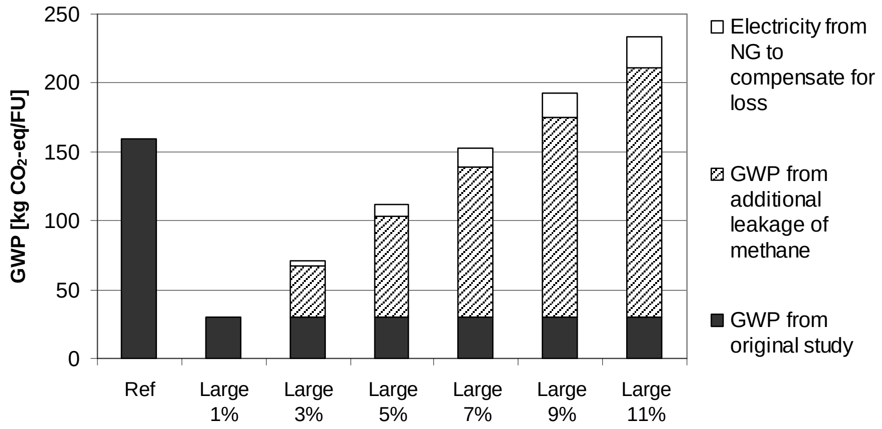

Figure 14: Impact from methane leakage on GWP in scenario Large

If the large scale scenario has a methane leakage of 7% - 9% of the produced gas, all the gain of producing biogas instead of just incinerate the OFMSW is lost, see figure 14. The same is valid for the medium scale plant, se figure 15. If the small scale biogas scenario reaches a methane leakage of just over 5% the gain in GWP compared to incineration is lost, see figure 16.

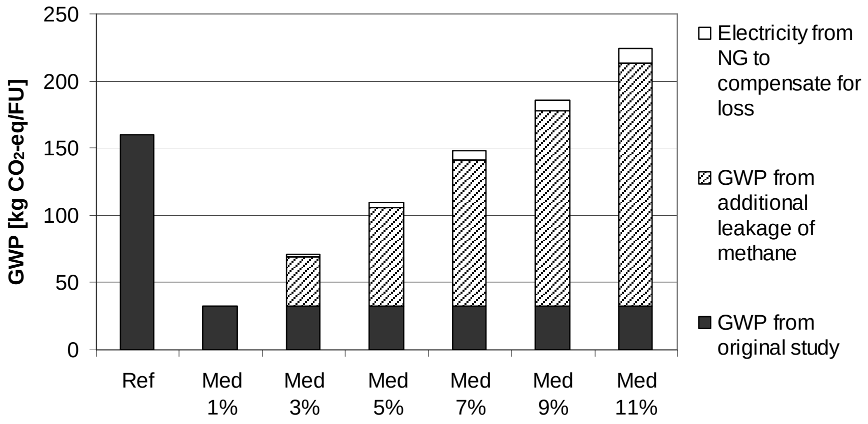

Figure 15: Impact from methane leakage on GWP in scenario Medium

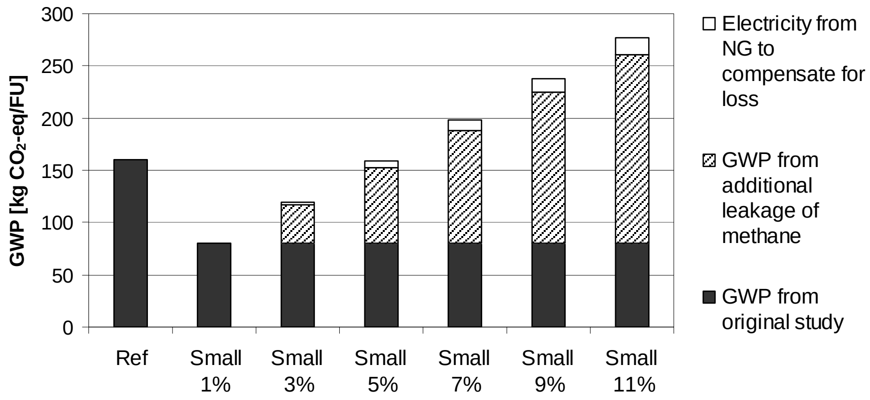

Figure 16: Impact from methane leakage on GWP in scenario Small

6.2 Transport of soil improver

The environmental impacts from the transports are quite big in all the scenarios. The transport of compost is the one transport that could vary very much, depending on the demand of soil improver. If the soil improver could be used in Singapore the transport would be neglect able and the emissions would decrease for all the biogas scenarios.

A change in transport distance for the compost might change the result significant. Listed in table 20 are the needed changes in transport distance for the compost to reach the same impact levels as the incineration scenario. The compost in the large scale scenario has to be transported additionally 235 km for the scenario to reach the same level of eutrophication as the reference scenario; the same figure for the medium scale scenario is 295 km and for the small scale scenario 410 km. For acidification the distance has to increase much more to reach the incineration level, and for GWP the transport distance has to reach quite unreasonable dimensions to reach the same level as incineration.

Table 20: Change in transport distance for the compost to reach the same impact levels as the incineration scenario

	Change in distance to reach same level as incineration [km]		
	Large	Medium	Small
GWP	4194	4111	2580
Acid.	660	720	833
Eutroph.	235	295	410

7 Biogas as a vehicle fuel

An alternative to the use of biogas for electricity generation is to use it as a vehicle fuel. To be able to do that it is necessary to upgrade the biogas to a higher methane content. Usually the methane content should be at least 97%. During the upgrading process the gas is cleaned from impurities, usually by a scrubber, and than compressed to a pressure of 250 bars.[95]

7.1 System boundary

To see if production of vehicle fuel is a better alternative than generation of electricity the system has been changed, the new system boundaries can be seen in table 21 and 22. Indirect environmental impacts have been taken into account in the same way as in the original study. For example is the amount of diesel that is replaced in the biogas scenarios added to the incineration scenarios and the electricity generated in the incineration scenario added to the biogas scenarios in form of electricity from natural gas. The output from each of the scenarios is 171 kWh/FU of electricity, 6.3 kg/FU of nitrogen, 3.3 kg/FU of phosphate and 1036 kWh of vehicle fuel.

Table 21: New system boundaries for the reference scenario

Included processes	Not included processes
– *Transport of waste to incineration plant* – *Incineration* – *Electricity used at the incineration plant* – *Oil used to start up combustion* – *Transport of ash to landfill* – *Production of fertilizer* – *Use of diesel in heavy vehicles*	– *Manufacturing of vehicles or machines used* – *Methane from landfill* – *Vehicles and machines used at the landfill site.* – *Production of diesel and fuel oil*

[95] Berglund & Börjesson (2003)

Table 22: New system boundaries for the biogas scenarios

Included processes	Not included processes
– *Transport of waste to biogas plant*	– *Manufacturing of vehicles or machines used*
– *Pre-treatment*	– *Treatment of waste water*
– *Anaerobic digestion*	– *Production of diesel*
– *Dewatering of residue*	– *Spreading of soil improver*
– *Composting*	– *Possible emission of methane from soil improver when back in soil.*
– *Transport of compost*	– *Production of natural gas*
– *Upgrading of biogas*	
– *Use of biogas in heavy vehicles*	
– *Electricity from natural gas*	

a Not included for small scale scenario, since there is no transport of the OFMSW

When upgrading the biogas instead of generating electricity in a gas turbine, the electricity needed for the biogas production must be taken from the grid instead. This leads to increased emissions of fossil CO_2 and other emissions such as NO_x and SO_2. Some of the biogas must be combusted in a furnace to heat the biogas reactor, which makes the net out put of biogas smaller.

7.2 Inventory

7.2.1 Reference scenario

The reference scenario is only changed by two parameters. No electricity from natural gas has to be added to the scenario; instead the use of diesel has to be added in order to compensate for the produced biogas in the biogas scenarios. In table 23 the emissions from the use of diesel in heavy vehicles are listed.

Table 23: Energy in used diesel and emissions due to use of diesel in heavy vehicles

Emissions[96]		
NO_x	2.69	kg/FU
SO_x	5.97	g/FU
CO	41.0	g/FU
HC	41.0	g/FU
CO_2	272	kg/FU
N_2O	11.2	g/FU
CH_4	22.4	g/FU
Energy		
Diesel	1036	kWh/FU

[96] Uppenberg et al. (2001)

7.2.2 Scenario Large and Medium

For the large and medium biogas scenarios the inventory data for the collection and the transport of compost are the same as in the original study. To this data, new data on upgrading, use of biogas in heavy vehicles, biogas combusted for heating, electricity from natural gas at the plant and electricity from natural gas, corresponding to the amount of electricity generated in the incineration, has to be added.

In table 24 the emissions from upgrading of the biogas are listed together with the amount of electricity that is needed. The emissions originate from the use of electricity from natural gas. In table 25 the emissions from using the produced biogas in heavy vehicles are listed.

Table 24: Electricity use and emissions from upgrading

Emissions[97]		
CO_2(fossil)	26.9	kg/FU
CO	11.8	g/FU
No_x	49.0	g/FU
SO_2	0.408	g/FU
HC	0.408	g/FU
CH_4	1.63	g/FU
CH_4 leakage	0.764	kg/FU
Energy		
Electricity[98]	53.4	kWh/FU

Table 25: Energy in produced biogas and emissions due to use of biogas in heavy vehicles

Emissions[99]		
NO_x	623	g/FU
CO	6.27	g/FU
HC	15.7	g/FU
CO_2 (bio)	214	kg/FU
Energy		
Biogas	1036	kWh/FU

[97] Börjesson & Berglund (2007)
[98] Nilsson (2001)
[99] Uppengerg et al. (2001)

Because there is no heat production when upgrading the biogas instead of generating electricity, some biogas has to be combusted to heat the biogas reactor. The emissions caused by this are listed in table 26. In table 27 and 28 the emissions from the production of the biogas are listed. Since the electricity can not be taken from the plants the electricity originates from natural gas. In table 29 the emissions from generating the same amount of electricity as in the incineration scenario, from natural gas, are listed.

Table 26: Heat use and emissions from heating in scenario medium and large

Emissions[100]		
CO_2(bio)	29.0	kg/FU
CO	5.93	g/FU
No_x	3.56	g/FU
SO_2	2.13	g/FU
Energy		
Heat	88.9	kWh/FU

Table 27 Electricity use and emissions at the large scale biogas plant

Emissions[101]		
CO_2 (fossil)	15.9	kg/FU
CO	6.00	g/FU
NO_x	29.0	g/FU
SO_2	0.241	g/FU
HC	0.241	g/FU
CH_4	0.965	g/FU
CH_4 (leakage)	859	g/FU
Energy		
Electricity	31.5	kWh/FU

Table 28 Electricity use and emissions at the medium scale biogas plant

Emissions[102]		
CO_2 (fossil)	21.5	kg/FU
CO	9.43	g/FU
NO_x	39.0	g/FU
SO_2	0.325	g/FU
HC	0.325	g/FU
CH_4	1.30	g/FU
CH_4 (leakage)	859	g/FU
Energy		
Electricity	42.5	kWh/FU

[100] Uppengerg et al. (2001)
[101] Börjesson & Berglund (2007)
[102] Börjesson & Berglund (2007)

Table 29: Amount of electricity and emissions from combustion of natural gas

Emissions[103]		
CO_2(fossil)	86.6	kg/FU
CO	38.0	g/FU
No_x	157	g/FU
SO_2	1.31	g/FU
HC	1.31	g/FU
CH_4	5.25	g/FU
Energy		
Electricity	171	kWh/FU

[103] Börjesson & Berglund (2007)

7.2.3 Scenario Small

For the small scale biogas scenario the same changes has to be done as in the medium and large scale scenario. In table 30 the emissions from upgrading are listed, the emissions comes from use of electricity from natural gas. In table 31 the emissions from heating of the biogas reactor are listed.

Table 30: Electricity use and emissions from upgrading in scenario small

Emissions[104]		
CO_2(fossil)	24.8	kg/FU
CO	10.9	g/FU
No_x	45.2	g/FU
SO_2	0.376	g/FU
HC	0.376	g/FU
Particulates	0.182	g/FU
CH_4 leakage	0.705	kg/FU
CH_4	1.51	g/FU
Energy		
Electricity[105]	49.2	kWh/FU

Table 31: Heat use and emissions from heating in scenario small

Emissions[106]		
CO_2(bio)	48.9	kg/FU
CO	10	g/FU
No_x	6	g/FU
SO_2	3.6	g/FU
Energy		
Heat[107]	150	kWh/FU

In table 32 the emissions from the production of the biogas are listed. The electricity comes from natural gas, since it can not be taken from the plant.

[104] Börjesson & Berglund (2007)
[105] Nilsson (2001)
[106] Uppengerg et al. (2001)
[107] Berglund & Börjesson (2003)

Table 32: Electricity use and emissions at the small scale biogas plant

Emissions[108]		
CO_2(fossil)	3.33	kg/FU
CO	1.46	g/FU
NO_x	6.06	g/FU
SO_2	0.0505	g/FU
HC	0.0505	g/FU
CH_4	0.202	g/FU
CH_4 leakage	859	g/FU
Energy		
Electricity	23.8	kWh/FU

Because there is less biogas produced in the small scale scenario, due to the large amount of biogas used for heating, the electricity needed for upgrading is less than in the large and medium scale scenarios. Emissions from the use of the produced biogas in heavy vehicles are listed in table 33.

Table 33: Energy in produced biogas and emissions due to use of biogas in heavy vehicles

Emissions[109]		
NO_x	574	g/FU
CO	5.78	g/FU
HC	14.4	g/FU
CO_2	198	kg/FU
Energy		
Biogas	955	kWh/FU

Because scenario small produces less biogas than scenario large end medium, the use of diesel in heavy vehicles, corresponding to this difference in output must be added. The emissions from the use of diesel in heavy vehicles can be seen in table 34.

[108] Börjesson & Berglund (2007)
[109] Uppengerg et al. (2001)

Table 34: Energy in used diesel and emissions due to use of diesel in heavy vehicles

Emissions[110]		
NO_x	0.209	kg/FU
SO_x	0.465	g/FU
CO	3.194	g/FU
HC	3.19	g/FU
CO_2	21.2	kg/FU
N_2O	0.871	g/FU
CH_4	1.74	g/FU
Energy		
Diesel	80.8	kWh/FU

The use of natural gas to produce the same amount of electricity as in the incineration scenario is also added to the small scale scenario. These emissions can be seen in table 29.

[110] Uppengerg et al. (2001)

7.3 Impact assessment

7.3.1 Energy use

When it comes to energy use, the heat use and diesel use in the scenarios are the same as in the original study, not including the indirect use of energy, such as use of diesel in heavy vehicles to replace biogas. The electricity use in the biogas scenarios has however changed due to the upgrading. In figure 17 the electricity use of the different scenarios can be seen. The medium scale biogas scenario uses the most electricity, followed by scenario large and incineration. The small scale scenario uses least electricity due to the small electricity demand at the plant.

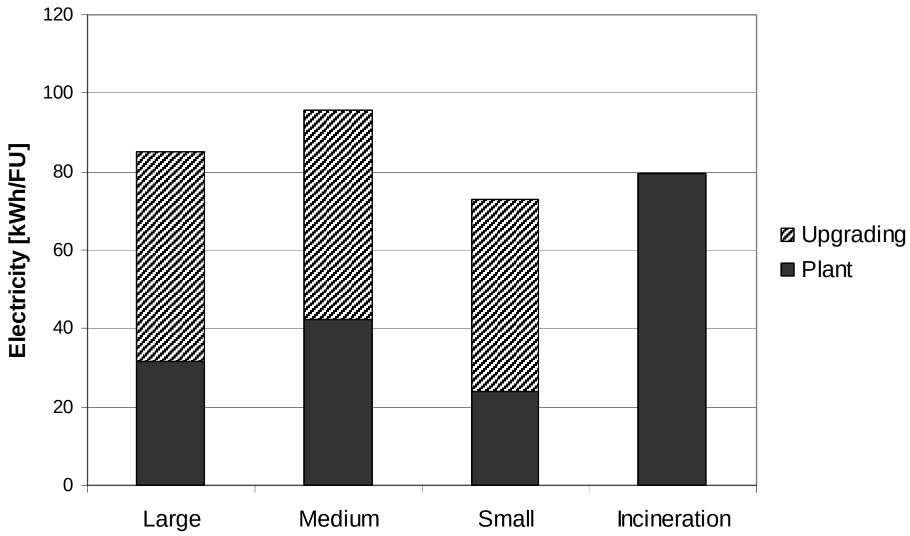

Figure 17: Electricity use in the different scenarios, when upgrading is done

7.3.2 Global warming potential

In figure 18 the GWP from the scenarios is shown. The incineration scenario has the highest GWP and this originates mainly from the use of diesel in vehicles. The small scale biogas scenario has higher GWP than the other biogas scenarios because of the high heat demand which cause a lower net output of biogas that can be used in vehicles.

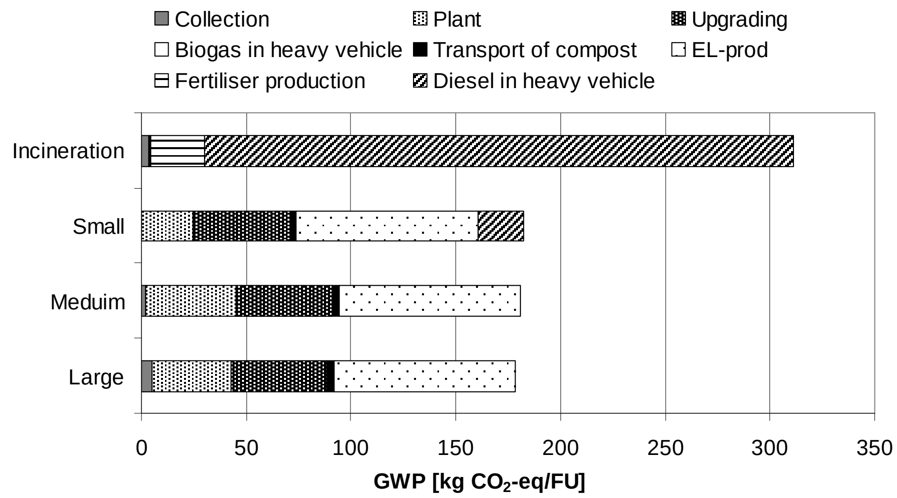

Figure 18: GWP from the scenarios when biogas is used for vehicle fuel.

7.3.3 Acidification and Eutrophication

Also for acidification and eutrophication the highest impacts comes from the incineration scenario, see figure 19 and 20 respectively. The use of diesel in heavy vehicles is the parameter that causes the greatest impact. This is because combusting of diesel emits high levels of NO_x. In the biogas scenarios the use of the biogas in heavy vehicles contributes the most to both acidification and eutrophication. This is because of the quite high levels of NO_x when combusting biogas.

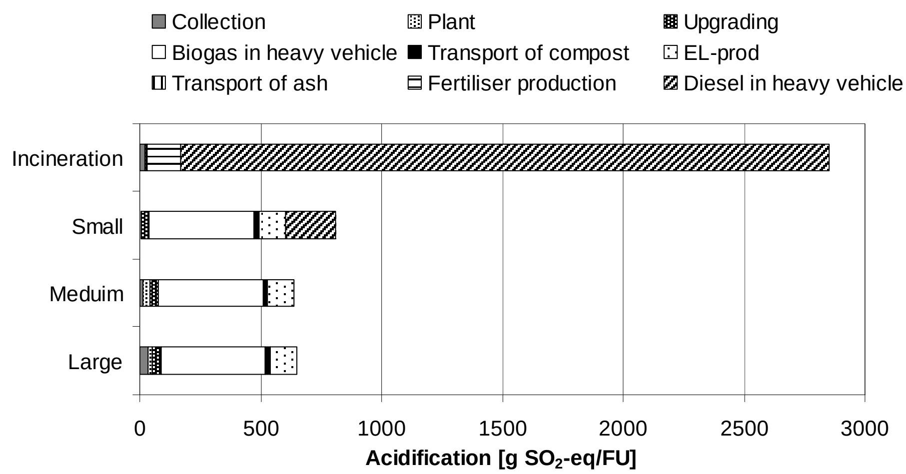

Figure 19: Acidification from the scenarios when biogas is used for vehicle fuel.

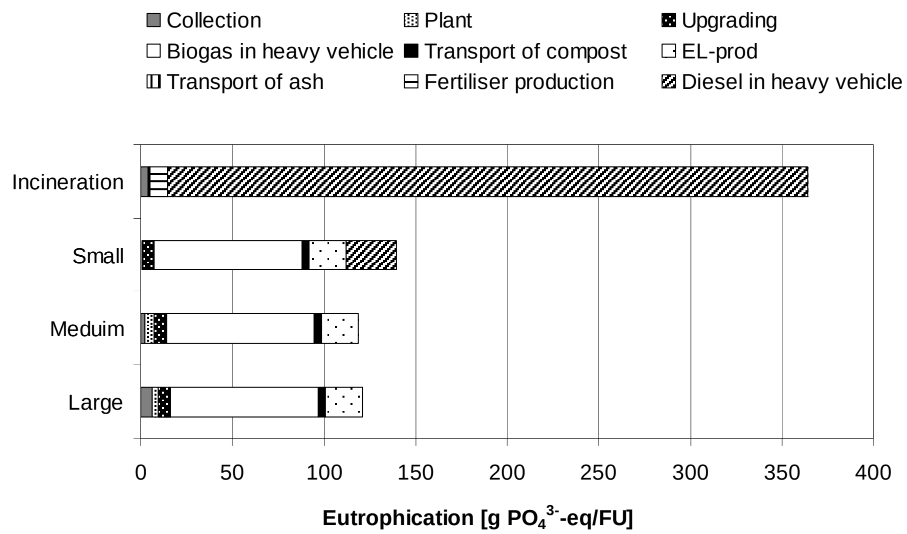

Figure 20: Eutrophication from the scenarios when biogas is used for vehicle fuel.

8 Discussion and conclusions

The most important thing to remember about these results is that they are 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 to uncertainty in the results is the data quality. In this study a lot of the data comes from foreign literature and facilities outside Singapore which means that there is no way to be sure that the data is valid for a Singapore context. However, there is still reason to believe that the results of the study are valid, since a lot of the data should not be site specific.

8.1 Original study

8.1.1 Emissions

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 CO_2-eq/FU than the medium and large scale scenarios and about 80 kg CO_2-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 production of fertilizer and 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 where everything is recovered. For acidification the large, medium and small biogas scenarios generates about 130 g SO_2-eq/FU, 140 g SO_2-eq/FU and 160 g SO_2-eq/FU less than the reference scenario respectively. However the biogas scenarios and incineration had about the same impact on eutrophication, the biogas scenarios had only about 8 g PO_4^{3-}-eq/FU -15 g PO_4^{3-}-eq/FU lower eutrophication than the reference scenario, which is because the combustion of biogas gives high emissions of NO_x.

It is of utmost importance to prevent leakage of methane at biogas plants, as can be seen in 6.1. Methane leakage has very big impact on the GWP from biogas systems. When biogas is leaking; methane alone will determine the GWP of the biogas system. Therefore leakage of biogas must be controlled and carefully monitored on a biogas plant.

8.1.2 Energy Use

When it comes to energy use the incineration plant uses the most electricity and has a lower electricity output then all the biogas plants. The net output of electricity from incineration of OFMSW is only about 40 % of that from the large or the medium scale biogas plant. The small scale biogas plant has also a much higher electricity output than the reference scenario. But the data on electricity use at the small scale plant is a quite uncertain figure, since the data is actually data from a farm scale biogas plants for e.g. ley crops or straw, not for OFMWS. Due to the trouble to find data on electricity use when producing fertilizer, only the electricity use at the plants is included. There is data that shows that there is a quite large amount of energy used when producing fertilizer[111,112], but the data does not say anything about how much of this energy that is in the form of electricity.

The small scale scenario has the lowest diesel use, because it has the shortest transportation distances. Since Singapore has such small land area, the collection distances will probably stay quite short, but the sensitively analysis in 6.2 shows that the transportation of the composted material might have an impact on the results. Before starting up a biogas plant, one has to be sure that there is a buyer of the compost/fertilizer and that this buyer is not to far away. The best option would be to use as much as possible of the soil improver in Singapore.

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 use is not a big issue, since waste heat is not usually sold. But when building a biogas plant, this can be strategically placed near an industry that is in need of steam, so that the waste heat can be utilized.

8.1.3 Land Use

The data on land use that was recovered during this study might say something about how much land that would be needed for the different facilities, but the data on the medium and small biogas plants are not valid for Singapore. The data is taken from biogas plants in Sweden, where there is no lack of land area to use, as is the case for Singapore. Especially for the small case scenario the data on land use is uncertain, since the owner of the biogas plant is a farmer who does not have to pay for the land used, since he was already the owner of the land when he built the plant.

[111] Börjesson & Berglund (2007)
[112] Ahlgren et al. (2008)

8.1.4 Scale

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 of the waste to a centralized plant is very long and there is no lack of land area to build on. In Singapore the transport distances will always stay quite short simply because of the small land area. In cold climates, where there is a demand for heat, a small facility can be utilized in a better way, since all the waste heat can be used, which means the low conversion efficiency to electricity is not such a big problem.

8.2 Biogas as a vehicle fuel

8.2.1 Emissions

In this study the biogas scenarios also had less environmental impacts than the reference scenario, for all emission categories. The difference between the biogas scenarios and the reference scenario was bigger here then in the original study. 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 such high amounts of emissions. Even though both diesel and natural gas are fossil fuels, diesel has higher emissions of GHG, NO_x and SO_x. In this case the reference scenario also gives about 130 kg CO_2-eq/FU more than the biogas scenarios. For acidification and eutrophication however the difference is big. The reference scenario generates about 2 kg SO_2-eq/FU more than the biogas scenarios and about 0.2 kg PO_4^{3-}-eq/FU more than the biogas scenarios. If only looking into GWP the biogas might be used either for electricity generation or as a vehicle fuel. But when looking into acidification and eutrophication the use of the gas as a vehicle fuel gives much higher environmental gain. The differences in GWP, acidification and eutrophication is 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, that biogas is best utilized in vehicles.[113,114]

One problem that exists in both studies is the leakage of methane. If the leakage of methane gets to big; the gain in GWP when using AD instead of incineration is lost. Upgrading usually causes higher losses of gas than the

[113] Börjesson & Berglund (2003)
[114] ADEME (2007)

production of the gas, why the upgrading plant must be monitored as well as the biogas plant.

8.2.2 Energy Use

The negative aspect is that the electricity input is higher for two of the biogas scenarios than for the reference scenario, but it is not a very big difference. The reference scenario uses less electricity than scenario large and medium. However, the electricity use shown in figure 17 includes only the electricity used at the plants. Data on electricity use for production of fertilizer has not been found. Scenario small uses the least electricity, but as for the original study, this is a quite uncertain figure, since the data on electricity use at the small scale plant is actually data on electricity use on a farm scale biogas plant for e.g. ley crops or straw.

8.2.3 Distribution and use of the biogas

A problem with the use of biogas in vehicles is the distribution of the fuel. In Sweden this problem sometimes is solved by the use of biogas in local busses, instead of in other commercial vehicles or in personal cars. The local busses can go to the same place every day to refill so that the distribution does not have to be a problem. In Singapore there are already some buses running on compressed natural gas (CNG), in these buses upgraded biogas might as well be used. Since Singapore struggles to keep emission levels down also on a local level, not only GWP should be considered. Most probably, the use of biogas in vehicles will reduce emissions of particulates, since diesel produces 11 particulates/MJ fuel and biogas less than 0.002 particulates/MJ fuel.[115] Thus, the use of biogas in heavy vehicles, such as buses, might help significantly to achieve cleaner air in Singapore.

8.2.4 Scale

In this study scenario small has a higher environmental impact for all categories than scenario medium and scenario large. This is because of the low efficiency on the small plant. Since biogas is used for heating, and the heat demand in the small plant is much higher than in the two other scenarios, the output of biogas is lower for scenario small.

[115] Uppenberg et al. (2001)

8.3 Suggested further studies

This study gives an overall view on how OFMSW should 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 that is leaking from biogas plants and where in the process the leakage takes place.

Another area that needs further investigation is the composition of the OFMSW in Singapore, to be able to predict biogas yields and 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 economical perspective, economical 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 to collect the organic waste and to encourage citizens to source sort their household waste. This is very important since the source sorting of the waste is necessary to make any treatment of OFMSW possible.

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E-mail correspondence with Krister Andersson, Hagavik Biogas plant

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E-mail correspondence with Wong Chak Huat, NEA

Appendix 1 – Methane yield

Table 35 Methane yields from different studies

Reference	Methane yield [m^3/kg VS]	Methane yield [m^3/kg TS]	Comment
Rintala & Ahring (1994)	0.588	0.529	Thermophilic digestion of OFMSW
Zhang et al. (2007)	0.435	0.371	Thermophilic digestion of OFMSW
Del Borghi et al. (1999)	0.36	0.27	Thermophilic digestion of 50% OFMSW and 50% sewage sludge
Berglund & Pålsson (2003)	0.51	0.46	Theoretical calculation
Berglund & Pålsson (2003)		0.35	calculation, ORWARE[b]
Davidsson et al. (2007)	0.336	0.292	Thermophilic digestion of OFMSW

a. The calculation is based on the carbon content in OFMSW, it is not based on input from Singapore. For details about how to perform the calculation see Berglund M (2003), Bilaga 1, p. 1.
b. The calculation is based on a sub model in the simulation model ORWARE (ORganic WAste REsearch) For details about how to perform the calculation see Berglund M (2003), Bilaga 1, p. 3.

The biogas yield that I have chosen to use in my study is an average of the values in table 35. However, I have chosen not to count in the value from Del Borghi, since it is the result from digestion of both OFMSW and sewage sludge and it the article is not very clear on if the value 0.36 m^3/kg VS is the methane production or the total amount of gas produced (including CO_2).

The average value that is used in this study is 0,40 m^3/kg TS.

Appendix 2 – Heat use at biogas plants

The values for heat use in the biogas scenarios are taken from Börjesson (2006). In that study the biogas production takes place under mesophilic conditions in Sweden. I have used this value in my study based on the assumption that the heat used in Sweden in a mesophilic process, is approximately the same as the heat used in a thermophilic process in Singapore. This assumption is based on the fact that the given the same mass and the same specific heating value for the two substrates, the heat energy needed only depends on how many degrees the substrate has to be heated.

In southern Sweden the yearly mean temperature is 6 °C – 10 °C and the substrate in the mesophilic process is heated to 37°C. This means the substrate has to be heated around 29 °C. In Singapore the yearly mean temperature is 27.5 °C and the substrate has to be heated to 55 °C, which means it has to be heated 27.5 °C.

To verify this I have done some calculations on the heat needed to heat the substrate in Singapore. No heat losses are included. The specific heating value of the waste (TS) is assumed to be 1.0 MJ/ton °C.

$E =$ heat energy needed	[MJ]
$m =$ mass of substrate	[ton]
$C_{p,mixture} =$ specific heating value of substrate	[MJ/ton °C]
$C_{p,water} =$ specific heating value of substrate	[MJ/ton °C]
$C_{p,waste} =$ specific heating value of the waste	[MJ/ton °C]
$T_{op} =$ operating temperature for biogas process	[°C]
$T_{air} =$ yearly mean temperature of air	[°C]

$$E = m \cdot C_{p,mixture} \cdot \Delta T \qquad \text{Eq. X}$$

$$C_{p,mixture} = \frac{(100 - TS) \cdot C_{p,water} + TS \cdot C_{p,waste}}{100} \qquad \text{Eq. X}$$

$$\Delta T = T_{op} - T_{air} \qquad \text{Eq. X}$$

$$C_{p,mixture} = \frac{(100-10)\cdot 4.18 + 10\cdot 1.0}{100} = 3.862$$

$$\Delta T = 55 - 27.5 = 27.5$$

$$E = m \cdot C_p \cdot \Delta T \Leftrightarrow E/m = C_p \cdot \Delta T$$

$$E/m = C_{p,mixture} \cdot \Delta T = 3.862 \cdot 27.5 = 106.205$$

$$\Rightarrow 106.205 \cdot 3 = 318.615$$

Since the mixture feeded to the biogas reactor has a dry matter content of 10% and the raw material has a dry matter content of 30%, the heat use per functional unit is 319 MJ. The value from Börjesson (2003) is 320 MJ.

Based on this I have used the value for heat use for both the medium scale biogas plant and the small scale plant in Börejesson (2003).

Appendix 3 – Emitted CO_2 when burning biogas

The methane yield is 0,4 m^3 CH_4/kg TS which means that it is 0,12 m^3 CH_4/kg raw material since the TS content in the waste is 30%. This means that 1 ton of raw material corresponds to 120 m^3 CH_4. There is a 2% loss of biogas during the process, thus the real methane yield is 117,6 m^3 CH_4/ton raw material.

Assuming complete combustion of CH_4:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

The molecular weight of CH_4 and CO_2 is:

$M(CH_4) = 12 + 1 \cdot 4 = 16$ [g/mol]

$M(CO_2) = 12 + 16 \cdot 2 = 44$ [g/mol]

This means that combustion of 16 g of CH_4 gives 44 g of CO_2, the density of CH_4 is 0,716 kg/m^3, thus the combustion of 117.6 m^3 of CH_4 gives 232 kg CO_2.

$117.6 \cdot 0.716 \cdot \frac{44}{16} = 231.6$ [kg]

The biogas contains 70% CH_4 and 30% CO_2, the CO_2 will be emitted directly to the air, and must be added to the total CO_2 emissions.

The volume CO_2:

$117.6 \cdot \frac{30}{70} = 50.4$ [m^3]

The density of CO_2 is 1.977 kg/m^3 so the emitted CO_2 is

$50.4 \cdot 1.977 = 99.6$ [kg]

The total amount of CO_2 from the combustion of the biogas from 1 ton raw material is:

$99.6 + 231.6 = 331$ [kg]

Appendix 4 – Characterization factors

Table 36 Characterization factors

	GWP 100[116] [g CO_2-eq/g]	Acidification[117] [g SO_2-eq/g]	Eutrophication[118] [g PO_4^{3-}-eq/g]
CO_2	1		
N_2O	320		
CH_4	25		
NO_x		0.696	0.13
SO_x		1	
NH_3		1.88	0.35

[116] EDIP 1997, LCA center
[117] EDIP 1997, LCA center
[118] Rydh et al. (2002)

Appendix 5 – Estimation of transport distances

Collection route

Table 37 Data used to estimate the collection distance

		Unit	Reference
Population	4839400	persons	Statistics Singapore (2008), Key Annual Indicators
Average household size	3.6	pax/house hold	Statistics Singapore (2008), Key Annual Indicators
Households per house	24		Assumption
Amount of f&b outlets	4958		Singapore department of statistics (2006)
Total amount of domestic waste Singapore	1.5	million t/yr	MEWR (2007), solid waste management
Truck capacity	11.9	ton	Assumption
Singapore area	707.1	km2	Statistics Singapore (2008), Key Annual Indicators
Distance between pick up places	50	m	Assumption

Total amount of domestic waste per day: 1500000/365=4110 tons

Number of houses for pick up: 4839400/(3.6*24)=56012

Total number of stops for pick up: 56012+4958=60970

Total collection route distance: 60970*50=3048500 m=3049 km

Collection route per truck: 3049/(4110/11.9)=8.8 km

Transport to treatment plant

The transport for the large scale biogas was estimated to 25 km. In the large scale scenario the two plants are assumed to be placed in the same area. From this the other transport distances was estimated based on how many plants there are in the different scenarios. In the medium scale scenario there are 27 plants. The transport distance in this scenario is estimated to $25/\sqrt{27}$ that is about 5 km. For the incineration there are 4 plants, but two of them is situated in Tuas at almost the same place, the distance was estimated to $25/\sqrt{3}$ that is about 15 km.

Appendix 6 – Input data to NTM Calc

Table 38 Input-data to NTM Calc, collection in the reference scenario

Motor	Euro 2	
Distance	24	km
Truck size (max load)	14	tons
Average load rate	42.5	%
Fuel consumption	3.5	l/km
Transport in city	100	%

Table 39 Input-data to NTM Calc, transport of ash with truck

Motor	Euro 2	
Distance	11	km
Truck size (max load)	40	ton
Average load rate[a]	42.5	%
Fuel consumption	4.9	l/10 km
Transport in city	100	%

Table 40 Input-data to NTM Calc, transport of ash with boat

Boat	2000-8000	dwt
Distance	25	km
load	1400	ton
Average load rate[a]	30	%
Sulphur content in fuel	2.6	w%

Table 41 Input-data to NTM Calc, collection in scenario large

Motor	Euro 2	
Distance	34	km
Truck size (max load)	14	tons
Average load rate	42.5	%
Fuel consumption	3.5	l/km
Transport in city	100	%

Table 42 Input-data to NTM Calc, collection in scenario medium

Motor	Euro 2	
Distance	14	km
Truck size (max load)	14	tons
Average load rate	42.5	%
Fuel consumption	3.5	l/km
Transport in city	100	%

Appendix 7 - Electricity from incineration of food waste

Table 43 References on calorific value in food waste

	DM content [%]	Calorific value [MJ/kg]	Calorific value DM=30% [MJ/kg]
IUT Singapore	16	3.115	**5.8 (used in study)**
Davidsson et al.	27	5.805	6.6

Calorific value: 5.8 MJ/kg = 5800 MJ/FU = 1600 kWh/FU

Table 44 Calculation of electricity from OFMSW

Parameter	Unit	Ulu Pandan	Tuas	Senoko	Tuas S
Plant conversation efficiency[119]	%	10.3	14.1	16.0	21.5
Food handled[120]	FU/yr	68415	105732	149268	186585
Calorific value[121]	kWh/FU	1600	1600	1600	1600
Electricity from OFMSW	MWh/FU	11275	23853	38212	64185
Electricity per FU	kWh/FU	165	226	256	344
Average per FU	**kWh/FU**		**248**		

[119] UNFCCC (2006)
[120] UNFCCC (2006)
[121] UNFCCC (2006)

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