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# Abstract

This report aims to give a broad overview of the potential of using food waste for biofuel production in Norway. In 2010, Norway generated 1.5 million tons of wet organic waste (Statistics Norway, 2013). As of July 2009, Norway instituted a law against the landfilling of biodegradable waste (Section 9.4a of Waste Regulations). Therefore a plan needs to be enacted to deal with food waste. We are evaluating the hypothesis that this residual resource can be used to produce a biogas, providing a clean product for the transportation industry and therefore reducing its carbon footprint.

We evaluated the biological process and technological options to propose a design for a production plant, using anaerobic digestion to produce biogas and a sludge that can be used as fertilizer. We go into detail about why we have chosen each step of the process. We also discuss in brief the environmental impacts of such a process and shift in energy use, assuming our product will in part supplant natural gas.

We have found that Norway has immense potential for using biogas from waste food. The technology is already in existence to do the conversion, the supply of food waste is more than adequate, there is a market available and our proposed plant is economically feasible. Also the environmental benefits are notable, which will also give our product value in the transportation market and benefit the local and international environment.

 This will also ease the pressure on municipalities to deal with food waste which can no longer be placed in landfills due to regulatory requirements.

We recommend that plants be built to service the larger towns in Norway such as Trondheim, Bergen and Stavanger and capacity increased in Oslo if the feedstock supply is adequate.

# Preface

For our project report we decided to produce a scientific paper directed at the technical community which is interested in the biofuels. We assume that they have some technical background but have tried to explain how we choose our process among the different technologies and techniques. We were able to use the skills and expertise of all members through this report and the website that was developed. We had members from Chemical Engineering, Biotechnology, Telematics and Industrial Ecology. Therefore we included in our report sections on the chemical processing (Vahid and Aqeel), biological processes (Ly and Bhim), environmental impacts (Samantha) and Zekarias created a website to share our findings, though it has not yet been published. Zekarias also used his organizational and management skills in the position of permanent manager.

# Profile Background

My name is M. Samantha Peverill, I am Canadian and a native English speaker. Here in Norway, I am doing a Masters of Science in Industrial Ecology. My bachelor’s degree is in Business and Environmental Studies. In addition, the expertise that I bring to the project includes an interest in food issues and environmental impacts.

My name is M.Vahid Sarfaraz, I come from Iran and my first language is Persian. I am not fluent in English as a second language. I am studying chemical engineering at the Masters level and my background is the same. I have no background with biofuels directly but I have a good background in processing, reactor design and economic analysis.

I am Zekarias Teshome; I was born in the capital city of Ethiopia, Addis Ababa (english translation new flower). My native language is Amharic; English is my second language. I studied Electrical Engineering while I was doing my Bachelor Degree. Here at NTNU, I am doing my Msc in Telematics. I am interested working in technology and biofuel is one of the renewable energies that we can use to support the planet, that’s why I made it my second village choice.

I am Aqeel Hussain and I am from Pakistan. I did my Bachelor in Chemical Engineering at the University of the Punjab Lahore Pakistan. To give international exposure to my education, I moved to Norway to study an M.Sc Chemical Engineering at the Norwegian University of Science & Technology. I contributed in EiT project while working on estimation of biogas production and focussing on safety issues of biogas plant.

My Mother tongue is Urdu and I also have good English language skills.

My name is Trinh Thi Truc Ly. I have my bachelor degree from the Department of Biotechnology at International University (Ho Chi Minh City - Viet Nam) and now I am doing my master thesis in Marine Coastal Development at NTNU.

I am Bhim Subedi and I am from Nepal. Being Nepali I am used to communicating in the Nepalese language, therefore I am not so fluent in English. I have completed my Bachelors in Biotechnology and perhaps that may be the reason I am feeling quite comfortable with Biofuel in EIT.

# Introduction

According to the World Energy Outlook (2012), the transportation sector is responsible for more than 50% of the global consumption of oil and this share increases as the number of passenger vehicles reaches towards the projected 1.7 billion worldwide by 2035. Transportation is responsible for 23% of global CO2 emissions, with road transportation representing 74% (Kahn Ribeiro et al, 2007).

This report aims to give a broad overview of the potential of using food waste for biofuel production in Norway. In 2010, Norway generated 1.5 million tons of wet organic waste (Statistics Norway, 2013). As of July 2009, Norway instituted a law against the landfilling of biodegradable waste (Section 9.4a of Waste Regulations). Therefore a plan needs to be enacted to deal with food waste. This residual resource comes from households, grocery stores, food processing and the service industries. There is still value that can be derived from this resource and we would like to contribute to the conversation on how best to use it.

The situation has the potential of being a win-win-win situation from an economic, societal and environmental perspective. It means reducing a waste stream and replacing some fossil fuel production, thereby lowering carbon dioxide emissions, carbon taxes and global climate change effects. Using food waste serves to avoid the land use and food price issues that face other biofuel feedstocks such as corn, because this resource is not currently productively used and should only compete with fossil fuel use.

Most of the world’s biogas systems operate in Europe (91%), with some in Asia (7%) percent and a few in the US (2%). Germany was the leader with 35% of all anaerobic digestion plants, Denmark next to Germany (16%) and Sweden, Switzerland and Austria all together 8% (Verma , 2002).

Norway’s first bio-waste treatment plant was launched by Cambi THP at Lillehammer started in December 1999 with a capacity of 14,000 tonnes of waste/year for producing electricity and steam. Oslo's new biogas plant is ready to launch, will treat biological food waste, and it is able to treat 50,000 tonnes of food waste a year. (CAMBI news, 2012)

This report will begin with an outline of supply considerations like the composition of wastes, origin and quantity available. We will present data based on research and consultation with experts regarding the average composition of this waste source.
Then we will give an overview of different chemical and biochemical processes, for example, anaerobic digestion. The organic compositions of waste foods and some other biodegradable substrates have to be treated by different methods to reduce their adverse impacts on the environment. Anaerobic digestion (AD) for biogas production is an effective bioprocess to achieve this goal.

Buswell’s Equation will be used to estimate the amount of biogas produced. This will be used for some economic analysis to determine whether this plant is economically feasible or not.
Finally we will look at the environmental impacts of this change, using a Life Cycle Assessment perspective.

Our discussion section will conclude with a brief outline of the practical considerations of putting this project into action. These insights were gained during the Technoport Entrepreneurship Seminar.

# Methodology

# 2.1 Supply of Feedstock.

In order to get an estimate of the amount of biogas we can produce from food waste in Norway, we need hard numbers of the amount of feedstock available, its composition and where it is produced. We decided that, for simplicity of logistics and information, initially we will not deal with agricultural residues, though it is a large portion of the biomass available. This allows room for our production to increase in the future. As shown in Table 2, Norway produces nearly 1.5 million tons of wet organic waste per year, using 2010 statistics (Statistics Norway, 2013). As mentioned we will exclude agriculture, and we will also neglect mining, electricity and construction industries. This leaves approximately 1.3 million tons of biomass available for biogas production in all of Norway. Obviously not all of this waste will be available for our purposes so this is used as the higher boundary of our feedstock supply range. At the moment this resource is diverted as shown in Table 1.

**Table 1. End of Life Treatment for Wet Organic Waste in Norway (Statistics Norway Waste Accounts, 2013)**

|  |  |
| --- | --- |
|  | **Units 1,000 tonnes** |
| Sorted for material recovery | 343 |
| Biological treatment | 297  |
| Energy recovery | 535  |
| Cover material | 8  |
| Incin without energy recovery | 159 |
| Landfill | 71 |
| Other | 79 |

**Table 2. Origin of Wet Organic Waste in Norway (2010)**

|  |  |
| --- | --- |
|  | **Units 1,000 tonnes** |
| Households | 556 |
| Agriculture | 110 |
| Mining | 5 |
| Manufacturing | 401 |
| Electricity | 1 |
| Construction | 73 |
| Service Industry | 346 |
| Absolute Total | 1493 |
| Total for us | 1303 |

As of July 2009, Norway instituted a law against the landfilling of biodegradable waste (Section 9.4a of Waste Regulations). As we can see from the 2010 statistics, there are exceptions to this and some material still goes to landfill.

To estimate the lower boundary of this resource we looked to information gathered by the ForMat project in Norway, which aims to decrease usable food waste by 25% by 2015 (ForMat, 2011). They have found that each person in Norway throws away 51 kg of perfectly edible food every year. They found 377,000 tons of total food waste but they do not include primary production, large households, hotels or restaurants. Also for our purposes it is not relevant that the food still be edible. Therefore these numbers represent an absolute lower boundary of our feedstock supply.

This waste is currently collected by either the municipality or private collectors that are paid by the grocer or restaurant.

We chose our estimates for supply by making several assumptions. We assume that we can gather up: 90% of the household food waste, 10% from service industry and 5% from manufacturing. This leaves approximately .46 million tons per year.

According to the ForMat report (2011), there are several categories of food waste that make up the majority. Milk and cream are the most often wasted, though they are emptied into the sink so that resource is not available for our purposes. Following dairy, the most wasted categories are fresh fruit, fresh vegetables, fresh baked goods and meal leftovers. Based on the 51.1 kg/person/year, fresh fruits and vegetables make up 12.5 kg/person/year, leftovers are 11.3 kg/person/year and fresh bread is 10.1 kg/person/year. This gives us an approximation of the composition of our food waste and allows us to choose appropriate biological tools and processes.

**Table 3. Wasted Usable Food, Norway, 2011 (ForMat, 2011)**

|  |
| --- |
| **Total wasted usable food: 377 000 tons** |
| **52 000 tons from producers** |
| **2 000 tons from wholesale** |
| **68 000 tons from retailers** |
| **255 000 tons from consumers** |

## 2.2 Characterization of Food Waste:

Food waste characteristics are key to anaerobic digestion because they govern the yield of biogas and the process stability. There are different types of waste food characteristics which are very important, such as volatile solids (VS), biodegradability, carbohydrate and lipid components, and Carbon to Nitrogen Ratio. Some of the characteristics of food waste given in literature are represented in Table 4 below (Qiao, W, 2011).

**Table 4. Characteristics of Food Waste (**Qiao, 2011**)**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | PH | TS% | VS% | VS/TS% | Fiber% TS | Lipid% TS | Proteins% TS |
| Food Waste | 4.41 | 19.71 | 17.04 | 86.45 | 20.2 | 29.9 | 17.3 |
| Fruit/Vegetable Waste | 4.06 | 9.15 | 7.72 | 84.37 | 35.2 | 12.9 | 15.2 |
| Sludge | 7.15 | 14.58 | 10.63 | 72.91 | 21.5 | 14.4 | 20.0 |

### 2.2.1 Biodegradability:

Food waste is typically biodegradable organic waste and therefore it can be converted into biogas. The biodegradability of food waste is due to presence of carbohydrate, lipid, cellulose and protein. The extent of biodegradability depends upon the relative amounts of each component. The yield and production of biogas is directly related to biodegradability (Khanal, 2010).

### 2.2.2 Carbohydrate and Lipid Contents:

The composition of food waste is determined by the type of food which is being discarded. This depends in turn on factors such as season and location. The composition affects our product, for example, the waste from a meat processing plant will contain high fat and protein content. The fat content are lipids and therefore less degradable and harder to digest. However, lipid content has a positive impact due to its very high energy content it will yield a high quantity biogas through digestion. When lipid contents are 20-30% it increases methane production rate by 7 to 15%. However if lipid content increases above 40%, the methagenosis is inhibited by long chain fatty acids, decreasing methane production. Food waste coming from the canning industry contains carbohydrates such as sugar and starch which are easily degradable (Khanal, 2010).

### 2.2.3 Carbon to Nitrogen (C/N) Ratio:

C/N ratio is an important factor for production of biogas from food waste. The presence of nitrogen is important in order to build up bacterial communities, which are essential for fermentation. A C/N ratio of 20-30 is optimum; if this ratio is higher it will negatively affect microorganisms. If the ratio is too low, nitrogen will come out from waste and accumulate at the top in the form of Ammonia, which increases the PH up to 8.5, which eventually affects methanogenic communities (Khanal, 2010).

## 2.3    Anaerobic digestion process description

## 2.3. 1 Pre-treatment

Pre-treatment is used to increase productivity and decrease hydraulic retention time (HRT). HRT has a direct impact on the size of the reactors. Pre-treatment process could be changed by varying the composition of the feedstock. Pre-treatment is divided into three main parts:

1. Size reduction
2. Separation
3. Mechanical hydrolysis

Different companies were reviewed and the detailed information extracted.

1. **Biologische Abfallverwertung GmbH & Co (Germany)**

<http://bta-technologie.de>

1. **Cambi**: Cambi <http://www.cambi.no>
2. **MemfoACT:**“MemfoACT <http://www.memfoact.no/>
3. **BioRefinex Canada Inc** <http://www.biorefinex.com/>

2.3.1 Size Reduction

Size reduction usually takes places in four different processes:

* **Grinding**
* **Maceration**
* **Pulverization**
* **Slurry**

### Based on the feed stock, one or a combination of these processes is used for pre-treatment. Grinding and maceration, involving cutting and shredding to pulverization and the reduction of feedstock to slurry in such equipment as a hydropulper. Since we use thermal hydrolysis before pulper, size reduction by grinding would be sufficient.

### 2.3.2 Separation

Separation is used to ensure that all feedstock is biodegradable and clean material. Non-biodegradable material takes up space and has a negative impact on HRT and size of the reactor.

Separation process for food waste usually contains three main steps:

* **Food Separation:** Separation in home, restaurant or food industry
* **Manual Sorting :** Remove inorganic material like rock and metal
* **Mechanical Sorters :** Screens, Rotating Trommels, magnetic separation.

In food processing plants, supermarket, restaurant, etc. Organic waste should be separated from non-degradable material. By using magnet, metal and rock will be separated. In a large amount of food waste manual sorting is time consuming and takes cost. While using mechanical sorting like screening will be helpful.

### 2.3.4 Mechanical hydrolysis:

Thermal pre-treatment (incineration) and mechanical biological pre-treatment are the most common methods for the pre-treatment of municipal solid waste. Thermal pre-treatment refers to the controlled burning of waste, sometimes including energy recovery. This method has increasingly been in use over the past few years mainly to reduce the amount of waste and to decrease biological activity. However, this method results in a much higher cost and the possibility of longer pay back periods because of high capital investment. Also, there remains public concern regarding the adverse health effects associated with the emissions from incinerators despite the fact that modern incinerators comply with current emission regulations.

We use thermal hydrolysis because it has many advantages compared to conventional methods, such as:

* Increased biogas production (can be as high as 65%)
* Energy savings through improved dewaterability after digestion
* Lower retention time and higher dry-solid content in digester which increases the capacity of the plant up to two or three times (TurbochargeYour Digester, n.d.).

## 2.4 Stages for anaerobic digestion

Anaerobic digestion is fermentative bioprocess in which organic matters are broken down by microbes in the absence of oxygen. During the process of biogas production by using anaerobic digestion, there are three main groups of microorganisms, including hydrolytic bacteria, acetogenic bacteria and methanogens (methanogenic bacteria) that have specific functions in hydrolysis, acetogenesis and methanogenesis stages, respectively. In the anaerobic digester, these three main processes occur simultaneously.

Therefore, the aim of this section is to introduce the biological processes which happen during these stages in biogas production.

There are some important parameters in anaerobic digestion that need to be discussed before going to detail in each stages, including pH, temperature, hydraulic retention time, organic loading rate and mixing condition.

* **pH**: the activities of microbes using in the anaerobic process are very sensitive to the changing of pH in its environment. Therefore, the pH value of system is completely influential to the final product yield. The formation of methane is highest when the pH is kept at narrow desired range of 6.5 to 8.5, with an optimum pH between 7 to 8. In case the pH in anaerobic digester is lower than 7 or higher than 8, production yield of methane may decrease (Weiland, 2010)

In order to keep the value of pH on the equilibrium, buffer has to be added into the system, such as sodium carbonate, calcium carbonate, calcium hydroxide, lime. The addition of selected chemicals should be done slowly to prevent any adverse impacts on the growth and activities of bacteria.

* **Effects of temperature on biogas production:** Methanogenic bacteria are inactive in very low or very high temperature. Futhermore, temperature determines the degradation rate of organic substances in hydrolysis and methanogenesis (Nayono, 2009).

There are two common optimal temperature ranges in which anaerobic fermentation can be carried out, mesophilic and thermophilic.

1. **Mesophilic** (optimal temperature around 25-40oC): The advantages of this system are more stable, easier to maintain, lower investment cost, does not need additional energy for heating the system. However retention time of the content is longer and biogas yield is lower
2. **Thermophilic (**50- 65oC): This process gives higher methane production and pathogen removal. However, this method is more sensitive to toxic substances (the amount of free ammonia increase with temperature) and harder to maitain, require additional energy for digester heating (Javad Asgari, 2011)
* **Hydraulic retention time (HRT):** is the average time that a substrate stays inside the digester before coming out.

The shorter the substrate is kept under appropriate conditions, the higher the risk of active bacterial population will be washed out while longer HRT gives more complete degradation of substrate, but requires larger volume of digester. Furthermore, the reaction rate in digester is also decreased with longer HRT, so it is necessary to find an optimal retention time for a substrate in order to achieve best benefits during production process (Yadvika, 2004)

* **Organic loading rate:** can be defined as the certain amount of organic matters (volatile solids or COD of feeding substrate) that are processed in anaerobic digester in a certain time.
* If the percentage of solids content is less than 15%, the system is known as “wet digestion”.
* If the amount of solids content is around 25-30%, the system is known as “dry digestion”

In both dry and wet digestion, water also needs to be added in order to lower the content of solids in digester (Nayono, 2009). The loading rate is strongly influential on gas production. Vartak et al (1997) was found that methane yield increase with reduction in loading rate. Besides, the rapid increase in loading rate is a potential risk of fatty acid accumulation in anaerobic digester, which leads to pH drop and reduces the activity of methanogenic bacteria or decreases the efficiency of the system. According to an experiment carried out on a 100 m3 biogas plant in Pennsylvania, if the loading rate of organic matters was changed from 346 kg VS/day to 1030 kg VS/day, gas production increased significantly from 67 to 202 m3/day. However, in case the increase in quality of organic substrates is beyond the optimal level of loading rate, no more gas will be produced.

* **Mixing condition:** Mixing can be considered as an important way to provide a sufficient contact between substrates and bacterial communities in digester system enables the reduction in particle size as digestion processes and help to release produced gas from the digester contents.

Mixing can be performed through several methods such as mechanical mixers, recirculation of slurry (digesting sludge), or by injection of the produced biogas.

### 2.4.1 Hydrolysis

Hydrolysis is the first process in anaerobic digestion that macro molecules such as proteins, fats, carbohydrates are converted into simpler and soluble molecules (peptides, saccharides, fatty acids…). This process is carried out by using some types of exo-cellular enzymes that are secreted by hydrolytic bacteria.

### 2.4.2 Acidification (or acid-forming stage)

The second step of anaerobic digestion is acidification that comprises two different steps of acedogenesis and acetogenesis which are effected by two strict anaerobic groups of acidogenic and acetogenic bacteria

Acidogenic bacteria are able to convert amino acids and sugars into volatile fatty acids, alcohols, aldehydes and gases like CO2, H2and NH3. (Figure 1). Among these products, the hydrogen, carbon dioxide and acetic acid will skip the acetogenesis stage and be used directly by the methanogenic bacteria to produce methane in the final stage(Nayono, 2009)

However, the rest of acedogenesis products will be transformed to hydrogen, carbon dioxide and acetic acid by acetogenic bacteria (Figure 1). In acetogenesis stage, it is important to keep hydrogen partial pressure at a low level in order to allow for the conversion reactions of acids occur in methane formation step (Javad Asgari, 2011).

Therefore, the final products of the acidification are acetic acids, hydrogen, and carbon dioxide that are used in the last step (methanogenesis) to produce biogas.



Figure 1: Anaerobic methane generation from organic materials (with microorgnasims involved) (Anaerobic Digestion Systems, 2009)

### 2.4.3 Methanogenesis (Methane formation)

In the last step of anaerobic digestion process, methanogenesis, the products of acidification process (mentioned in second step) are converted into methane and carbon dioxide.

The production of methane requires the presence of methane producing bacteria, called methanogens(Javad Asgari, 2011). These bacteria prefer an environment with strict anaerobic conditions for their growth, are very sensitive to the changing of environment and have the important function of converting hydrogen, carbon dioxide and acetic acid into methane and carbon dioxide (Javad Asgari, 2011).

During this stage, there is around 66% of methane that is produced from acetate and the fermentation of alcohol formed in the second stage by using acetoclastic methanogenic bacteria (*Methanosaeta spp*. and *Methanosarcina spp*.), and remaining 34% of methane is produced by using methanogenic bacteria to reduce carbon dioxide by hydrogen (Nayono, 2009). Table 4 indicates the bacterial groups that involved in each step of AD process.



**Table 5:** Types of bacteria involved in each step of organic material **digestion**

## 2.5 Estimation of Methane Production:

The production of biogas can be estimated from the food waste once we have some estimated formula for Food waste. The CH4 and CO2 contents then can be predicted from reaction derived from Buswell Equation (Curry, 2012). The Chemical formula for Food waste can be calculated from ultimate analysis of food waste. This is needed in order to estimate the biogas production. Ultimate Analysis of mixed food waste with some adjustment is given as follow. We estimated average values from literature.

**Table 6. Ultimate Analysis of Food Waste (**Curry, 2012**)**

|  |  |
| --- | --- |
| Component  | % |
| C | 51 |
| H | 12 |
| O | 34.6 |
| N | 2.6 |

Consider 100 kg of food waste, the composition of which is given above. Mole of Carbon, Hydrogen, Oxygen and Nitrogen are calculated as follows:

Moles of Carbon = 0.51/12 \* 100 = 4.25 Kg moles

Moles of Hydrogen = 0.12/ 1.008 \* 100 = 6.3 Kg moles

Moles of Oxygen = 0.346/16 \* 100 = 2.35 Kg moles

Moles of Nitrogen = 0.026 / 14 \* 100 = 0.185 Kg moles

Molar Ratio

C : H : O : N

4 .26 : 11.9 : 2.1 : 0.186

Dividing by Minimum value

C : H : O : N

 23 : 64 : 12 : 1

So the chemical formula for food waste calculated from ultimate analysis is given as C22H34O13N1. Now, the biogas yield can be theoretically estimated using this chemical formula by Buswell’s Equation. Buswell devised equation based on chemical formula to predict theoretical yield of component products from digestion. The Buswell’s equation is given as

$$C\_{a}H\_{b}O\_{c}N\_{d}+\left(\frac{4a-b-2c+3d}{4}\right)H\_{2}O\rightarrow \left(\frac{4a+b-2c+3d}{8}\right)CH\_{4}+\left(\frac{4a-b+2c+3d}{8}\right)CO\_{2}+DNH\_{3}$$

Putting the values of a, b, c and d as given by the formula C22H34O13N1, gives equation

C22H34O13N1 + 1.75 H2O -------------→ 16.6 CH4  + 6.7 CO 2 + NH3

Norway has 462100 tons per year of food waste for the population of 4.9 million estimated from assuming 80% organic waste from household and 5 % from service industry is food waste. The food waste estimated for 0.6 million population of Oslo is 56583 tons per year. So we have 95730 tons/year food waste for our plant which corresponds to 155 tons/day. Using literature value, 17 % of waste is volatile solids which are actually converted into biogas which correspond to value 26 tons per day.

Biogas production can be estimated for 26 tons per day from above calculated reaction of fermentation.

Mass of food waste entering = 26 ton/day = 26000 kg/day

Moles of C22H34O13N1 = 49 kg mole/day

Moles of H2O required = 365 kg moles/day,

Moles of CH4 produced = 638 kg moles/day ,

Moles of CO2 produced = 493 Kg moles/day,

Moles of NH3 produced = 49 Kg moles/day,

The corresponding volume of product gases is calculated using PV=nRT equation at standard conditions.

Volume of CH4 = 15604 m3/day

Volume of CO2 = 12071 m3/day

Volume of NH3 = 1202 m3/day

Buswell equation is a good tool to test the potential of biogas production but it gives less CH4 to CO2 ratio than the actual observed.

2.6 Post- Treatment:Bio gas contains carbon dioxide (CO2) and hydrogen sulfide (H2S) which is toxic and corrosive. It must be removed to enable the gas to be used for power generation or in a car engine. Sludge, which is the nutrient-rich solids left after digestion, can be used as a fertilizer. It needs some preparation before selling to customer.

### 2.6.1 Bio gas treatment:

1. **Hydrogen sulfide contents**

Hydrogen sulfide (H2S) in the biogas is a corrosive component which is usually removed by injecting a small quantity of air into the digester. Bacteria uses air and converts the toxic and corrosive H2S to elemental sulfur.

1. **Carbon dioxide contents:**

CO2 removal from bio gas is mandatory to meet the specifications of a natural gas grid since CO2 reduces the heating values of natural gas, is corrosive and increases the volume for storage and transportation of gas.

Table 7 .Bio gas composition [Rasi et al., 2007]

|  |  |  |  |
| --- | --- | --- | --- |
| **Process** | **Co2[%]** | **CH4[%]** | **H2s[ppm]** |
| **Farm biogas plant** | 37-38 | 55-58 | 32-169 |
| **Sewage digester** | 38.6 | 57.8 | 62.9 |
| **Landfill** | 37-41 | 47-57 | 36-115 |

As the table shows that direct usage of biogas after bio gas plant usually needs treatment, due to the content of CO2 and H2S. Nowadays biogas plants use Pressure Swing Adsorption (PSA) to reduce the sulfur content of the gas. Research results indicate that a membrane process with a CH4 recovery of 99% at a low variable cost with more environmentally friendly could be designed to achieve natural gas grid industry. (Deng, 2010). Makaruk et al. pointed out that a membrane system good compatibility within biogas plants in heat integration aspect (Makaruk, 2010). In 2008 MemfoACT began producing a membrane which has more focus on biogas recovery. (MemfoACT - unique membrane technology, n.d.)

**2.6.2 Fertilizer treatment:**

The sludge that remains as a byproduct must be treated in order to meet the standards of the fertilizer customer, such as those relating to moisture content. There are different methods to separate the liquid inside of the digested effluent depending on the feedstock.Here are some examples of methods used.

1. **Slope Screen Separator**

This is the cheapest but not the most effective way to remove solid residuals from liquid effluent. The method refers to simply allowing effluent to rundown the screening tilted plate.

1. **Centrifuge**

We use centrifugal force to dewater effluent based on the differences in density between the solid and liquid material. The use of centrifugal force makes this method more efficient for separation.

## 2.7 Reactor Design:

## 2.7.1 Single Stage vs. Multistage

There are three groups of microorganisms for each step in the AD process: fermentative bacteria, acetogenic bacteria and methanogens. Each group has a specific function in hydrolysis, acetogenesis and methanogenesis steps, respectively, in AD. In a conventional AD system, the steps of acidogenesis and methane formation occur in a single reactor that may lead to the reduction of pH. Furthermore, the microorganisms that we are using for these two steps require different optimal conditions for their growth. Therefore, it is a problem needed to be solved to get balance between them.

The separation of acetogenesis and methanogenesis into two different bioreactors was proposed to overcome this problem. If doing so, each group of microorganism will be provided an optimal environmental conditions for their growth and the stability of AD process will be enhanced and easier to control.

While single stage reactor is cheaper and simpler but it takes longer, generally 14 or 28 days depending on the feed and operating temperature (Verma et al., 2002).

Multi stage fermentation takes half as much time as single stage, although both method has the same quality. (Anaerobic Digestion Systems, 2009) Therefore we chose to use a single stage reactor.

### 2.7.2 Batch vs. Plug Flow vs. Continuous

An investigation was conducted into the suitability of either of the batch or continuous stirrer tank reactor (CSTR) digesters for anaerobic degradation of MSW in the production of biogas. Hilkia et al. state that the amount of methane produced per unit volume of the batch digester is about four times less than the amount per unit volume of the CSTR (Hilkia, 2008). Also the cost per unit volume of the batch digester ($5.98) is six times less than that of the CSTR ($33.8). So, we use the batch digester which is better option for the digestion of MSW for biogas production, compared to the CSTR.

## 2.8 Bio gas storage tank

There are two main types of storage tanks are used in biogas plants; internal and external. Internal is in low pressure and connected to digester while external is in high pressure and separated from the digester. High pressure makes safety and material costly, therefore we use low pressure connected storage tank to be more commercialized.

* 1. Proposed Design:

Our proposed design includes the whole process from food waste to biogas and fertilizer. Our supply is based on food waste which is gathered from households, restaurants and grocers and transported by truck to our plant, near the town. Non-biodegradable material is removed in separation pre-processing in two steps. First roll crusher will reduce the size of the particles which improves solubility, allows for better heat distribution and improves the efficiency of the digestion. Then small metal particles are removed from the system by passing through the magnet. Before feed goes to pulper oversized material, sand and floating material removed by screening and mixer. Steam will be recycled from the reactors and the flash tank to pre-heat the waste in the pulper. Pre-heated sludge is pumped into the reactor(s) where thermal hydrolysis at high pressure and temperature takes place at approximately 165ºC for 30 minutes (TurbochargeYour Digester, n.d.).

Thermal hydrolysis can prevent very unpleasant odors from food waste in the hydrolysis steps. In addition food waste in a pressure vessel, splitting the tough cell membranes of the microorganisms present, releasing and breaking down the long chain molecules, and making them readily digestible.

In a flash tank steam explosion disintegrates the organic material into easily digestible material. By using the thermal hydrolysis there is no need for because they are already digestible (TurbochargeYour Digester, n.d.).

Since we use hydrothermal treating waste mesophilic condition is more preferable. So they cool down to 40 C by heat exchanger to reach mesophilic condition.

Hydrolyzed waste goes into single batch reactor with temprature of 40 C and pressure a little less than amospheric pressure (0.2-0.8 atm) with the help of acedogenic bacteria, H2, CO2 and CH3COOH will be formed and the rest of acedogenesis will be transformed to hydrogen, carbon dioxide and acetic acid by acetogenic bacteria. During methagenasis stage, hydrogen, carbon dioxide and acetic acid are converted into methane and carbon dioxide. Compressed air is injected into the digester to avoid hydrogen sulfide. Digested hydrolyzed organic material is filtered by new carbon membrane Company MemfoACT with the ability to combine high selectivity and high productivity. This serves to reduce required membrane area and compression duty, therefore reducing the cost of gas. Sludge goes to centrifuge separation to remove the water to reach the fertilization industry standard. Filtered gas is sent to low pressure connected storage tank with 2 atm pressure to store for transporting or selling to customer which is cheaper and safer. Then biogas pressurized up to 100 bar to sell as a CNG to bus.



Figure 1. Process design flow sheet

## 2.9. Safety Consideration

Biogas is inflammable and can cause an explosion if not properly handled. Therefore much consideration must be paid to safety issues associated with Biogas production. Biogas plant is not feasible to build far from city area as its potential users like buses or domestic heating systems are in cities and it is not economical to transport it via long distance. So, preventive measures are of great focus to eliminate potential hazards for smooth running of plant.

Biogas is quite explosive if present in certain amount in air. Common flammable gases and their dangerous presence in atmosphere are given in table (Curry, 2012).

**Table. 8** Flammability Limit

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Biogas** | **Natural Gas** | **Propane** | **Methane** | **Hydrogen** |
| **% Volume** | **6 to 12** | **4.4 to 15** | **1.7 to 10.9** | **4.4 to 16.5** | **4 to 7** |

For biogas plant potential hazards zones are classified according to likelihood of explosion. These zones can be explained as

Zone 1: Explosive atmosphere which is continuous and often

Zone 2: Explosive atmosphere that is occasional

Zone 1 is not considered in operational running of plant for the production of biogas. Continuous and often explosive environment is prevented and cannot be allowed for the safe running of plant. Zone 2 occasional explosive atmosphere can be happened by accumulation of biogas due to some leakage or some other operational troubleshooting. To cope with Zone 2, proper ventilation is maintained to remove any accumulation of biogas.

The safety of biogas storage is also of great importance. The biogas storage can be built in open space or within a room with ventilation. The authors recommended open space storage capacity for this process with tight leakage control. The three meter around the storage capacity is considered to be Zone 2 and this area is focused to address any occasional explosion.

# 3. Results & Discussion

Considering 26 tons/day of organic food waste available in feed stream which can be converted into biogas by anerobic digestion. The organic food waste is represented by C22H34O13N1 calculated from ultimate analysis. The estimated product biogas contains CH4, CO2 and NH3.

**Table 9** Biogas Production

|  |
| --- |
| **Biogas Production** |
|  | Moles/day | Volume($\frac{m3}{d}$) | Volume % |
| CH4 | 638 | 15604 | 54 |
| CO2 | 493 | 12071 | 41.8 |
| NH3 | 49 | 1202 | 4.16 |

This estimation of biogas production showed that volume % of methane is larger than CO2 but still large portion of biogas contain CO2. The quantity of CO2 actually present in biogas is lower than what is calculated from Busswell equation. This is due to relatively high solubility of CO2 in water and part of CO2 can be associated with water forming chemical bond (De Mess, 2003). The CO2 is not energy source and its presence decreases the heating value of biogas. The calculation of biogas using ultimate analysis reveals that if % of H in ultimate analysis of organic mass is more in the % of CH4 in the biogas is increased.

The quantity of CH4 produced is less than what is estimated from Busswell Equation. Labatut provided comparison of different food waste with observed methane yield and yield calculated from Busswell Equation (Labatut, 2011).

Figure 2. Observed and estimated methane yield [A. Labatut ,et al.]

 The graph shows that vegetable oil has highest observed and estimated value from Buswell equation. Vegetable oil has high lipid contents which are high energetic and have potential to produce maximum biogas. Vegetable oil depicts large difference in yield estimated from Buswell’s equation and observed value which is due to less biodegradability of lipid contents. Cola beverage also indicates higher yield and cola beverage mostly consist of carbohydrates. Carbohydrates are most easily degradable which is evident from small difference in observed yield and estimated.

The rate of production of biogas with respect to time in days is given by Qiao and Yan. The graph shows that there is rapid increase in production of biogas during early days. The maximum increased is recorded within firs three days and it reached to value close to 750 mL/g-VS. After that the curve shows a smooth behavior and there is no rapid increase in production and on 15th day there is only small increased to reach value 750 mL/g VS. This result shows that the maximum digestion is carried out during early days (Qiao, 2011).



Figure 3. Rate of bio gas production[Wei Qiao. et al]

## 3.1 Business Plan

During the Technoport Seminar on Entrepreneurship we had the opportunity to create a rough business plan for our idea. This helped us see the practical considerations of the project. We will now outline some of the details that we discussed during this process. We began by brainstorming on who our potential customers could be, in Trondheim in particular since that is the region we know best in Norway. We will likely have different customers for our product (biogas) and our by-product (fertilizer). For our biogas we would like to sell it to the transportation industry for example, AtB, because the buses already run on natural gas. We believe that they would be very interested in our product because it can be marketed as a cleaner energy source than their current fuel, and this is a matter of importance for public transportation. Also, due to lower carbon dioxide emissions, they could realize a reduction in carbon tax paid. Our byproduct will be sold directly to farmers. We would like to establish continuous relationships with our customers.

One of the more difficult topics that arose was that of channels, meaning how we actually sell the product. We debated several options. They are as follows. We could have our customers (buses) come to our facilities to receive the product. This would require our production to be centrally located. Another option would be to sell the product to a company that has an existing distribution network and consider ourselves exclusively a producer, not a distributor. We determined that we would need to gather more information on the current setup before decisions could be made.

We examined the key resources that we have to determine what activities we should control. It was agreed that we possess interdisciplinary knowledge, organizational skills, a network revolving around NTNU and management skills. Key activities that we would control would include the conversion process, optimizing technology, research and design including new feedstocks and products and the production of our product and by product. Within Norway we would like to explore partnerships with NTNU, Sintef, UMB, Bioforsk and waste collection experts, to name a few. This would supplement our knowledge and our project could contribute to ongoing discussions about how best to use food waste.

In terms of funding, we would look for investors in addition to our product revenue streams. There is potential to charge for the collection of our feedstock, since it is something that supermarkets currently pay to have taken away. Also, due to the environmentally friendly nature of our idea, we believe that we may be able to secure some government funding.

Due to the short nature of the Entrepreneurship Seminar, we could only briefly discuss costs, but pointed out some of the major categories. This project would have very large start-up costs, as we would need to invest in building a production plant. Our running costs would include transportation of the feedstock and potentially the product, salaries and operational costs associated with running the plant.

This exercise was very helpful for us to see the practical application of our idea.



Figure 4. Business plan network

## 3.2 Economic Analysis

In 2005 Cambi AS made some analysis for constructing and operating a hydrolysis plant in Hamar which was 3.8 million Nok . They assumed production of 3600 t DS/year with a dry solids (DS) content of 16% .We try to use this data for estimating whether our plant is feasible or not. (Cambi Process, 2006)

### 3.2.1 Fixed Cost

Our plant with 9400 t DS/year feed and assuming 17% solids (DS) content which is double than Hamar feed. By using capacity index (Ludwig) and Cost index for year of 2012 we comes out with 5.7 million NOK for constructing and operating of our plant.

Exact calculations are presented in Appendix 1.

### 3.2.2 Variable Cost

For 2000/2001 the total fee for receiving, treatment and disposal for the Hamar plant was 2288.51 NOK/ t DS (Cambi Process, 2006).

### 3.3.3 Cash flow diagram

During the project, cash flows out of the company to pay for the plant construction. When the plant starts to operate after one year then revenue from selling the biogas flows back to company. Price of biogas is depends on the place which will sell. We assume to sell the biogas in Oslo which is a big city with 5.56 NOK/Nm3.By assuming 40 % tax rate in Norway we earning money after around 4 years which is feasible and interesting for investing.

Figure 5 Cumulative Cash flow diagram

## 3.3 Environmental Impacts of Process

It is widely recognized that through carbon dioxide emissions, fossil fuel use is contributing to global climate change and destabilization. According to Cherubini et al. (2011) using biomass for energy is one of the “most promising renewable energy alternatives.” There can be, however, challenges to using biomass due to the effects on changing land use and rising prices of agricultural goods. The practice of using a waste resource (such as food waste) effectively avoids these pitfalls and may offer a bridge solution while we develop other renewable energy sources and reduce the overproduction and wastage of food.

As discussed above, biogas production from food waste has the potential to reduce environmental impacts, in multiple ways. We have chosen to use the Life Cycle Assessment (LCA) method to evaluate the environmental impacts of this process and compare it to alternatives. LCA has become a popular method to evaluate bioenergy systems because it takes a holistic picture of the situation, considering direct and indirect emissions and effects of all activities involved in delivering a service. Therefore it allows us to identify “problem shifting”, the case where improvements are realized in one area, say carbon dioxide emissions, but performance in another area decreases, for example eutrophication.

In the past, LCA studies of bioenergy systems have used a global warming potential (GWP) factor of zero for biogenic CO2, effectively saying that it has no impact due to regrowth of the feedstock. (Cherubini et al, 2011) But in fact, this CO2 remains in the atmosphere during the period of regrowth of the biomass, having the same effects as anthropogenic CO2. Therefore it must be considered in part. Cherubini (p. 10, 2011) proposes a series of GWP factors to be used depending on the feedstock and time horizon. In our complete LCA study we would need to approximate the appropriate factor to determine our GWP impact.

There are three areas where we will consider environmental improvements:

- improvement over other fuel types, namely natural gas

- improvement over other management regimes for food waste

- improvement over other fertilizing regimes.

In theory we would like to calculate or estimate all of the impacts associated with the process, but in this report we will only give a brief overview and rough quantification. We will primarily focus on GWP because this is the measure relating greenhouse gas emissions to climate change and climate change is the main concern of the transportation sector. Biogas from food waste will be compared to natural gas to get an idea of comparative environmental impacts.

3.2.1 Biogas compared to Natural Gas

We chose natural gas due to our assumption that biogas will substitute natural gas used in transportation or district heating.

The emissions from the growth, processing and transportation of the food are not attributable to our product because the feedstock is not produced for our purposes, we are only taking advantage of inefficiencies within the food system. We need only to consider the emissions from the processing within our plant, operational emissions and the building of the plant itself. According to our preliminary calculations of output (see Appendix #2), through processing we emit 2.13 kg CO2 per kg biogas produced. This is the CO2 contained in the fuel, which we remove. Our membrane technology is very effective so we assume that methane is not leaked from the system into the environment. The carbon dioxide is removed entirely from the fuel so virtually none is released during combustion. We have not incorporated the emissions from building the plant, nor the upstream emissions of our energy use within the plant. We assume electricity used is generated from hydropower and therefore has a minimal CO2 contribution but given more time we would include everything. Using information from the Biomass Energy Centre in the U.K. (2013) we calculated the life cycle impacts of natural gas to be 4.02 kg CO2eq per kg natural gas. Details of these calculations can be found in Appendix 1.

3.2.2 Different Food Waste Management Options

A study done in the United States compared different ways of managing food waste with a focus on environmental impacts (Levis, 2010). Comparisons were made between composting, anaerobic digestion and landfilling. Anaerobic digestion was found to be the most environmentally benign process, with a net reduction of CO2 in the atmosphere. Their conclusion was that for every 1000 kg of food waste (plus 550 kg branches), 395 kg of CO2 is removed from the atmosphere. Some reasons for this are: the energy offset by the recovery of methane (considered to replace coal and natural gas) and the storage of carbon in the soil by way of the fertilizer byproduct. This is a very positive result, but it cannot be applied directly to our case. We are not replacing coal here in Norway so the offset will certainly be less. Also, we are not including branches in our process, though it is unclear how they will affect the environmental performance.

3.2.3 Offsets from Fertilizer

We assume that the use of our fertilizer by-product serves to offset the production of mineral fertilizers and peat extraction. These are often very polluting productions from a greenhouse gas perspective, especially the destruction of peatlands due to their role as a carbon dioxide sink (Strack, 2008).

## Conclusions

We have found that Norway has immense potential for using biogas from waste food. The technology is already in existence to do the conversion, the supply of food waste is more than adequate, there is a market available and our proposed plant is feasible. Also the environmental benefits are notable, which will also give our product value in the transportation market and benefit the local and international environment. From an industrial ecology perspective this project has the benefits of using renewable energy (food grown from the power of the sun) and also closing the loop on nutrients and energy instead of allowing a linear take-make-waste process to perpetuate.

 This will also ease the pressure on municipalities to deal with food waste which can no longer be placed in landfills due to regulatory requirements.

We recommend that plants be built to service the larger towns in Norway such as Trondheim, Bergen and Stavanger and capacity increased in Oslo if the feedstock supply is adequate.

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## Appendices

### Appendix 1

By assuming 38141915 NOK for 3600 t DS/d we can estimate the price for 9400 t DS/d.

$$C\_{2}=C\_{1}(\frac{Q2}{Q1})^{m}$$

C2= Price in desired capacity

C1=Old capacity

M= Capacity exponent which is usually around 0.6

$(\frac{Q2}{Q1})$= Capacity ratio

(Ludwig, pp 71)

$C\_{2}=38141915(\frac{9400}{3600})^{0.6}$= 57812326 NOK

For converting price from 2005 to 2012 by using Cost index method we have:

Cost in year A= Cost in year B$×$ ($\frac{Cost index in Year A}{Cost index in year B})$

Cost index in 2012= 1.6

Cost index in 2005=1.4

(Towler , pp, 337)

Cost in year 2012= 57812326$×$ ($\frac{1.6}{1.4})$= 61941777.86 NOK

Gross profit by generating 90971.32 Nm3 and assuming 5.56 NOK/Nm3 will be :

90971.32$×$5.56=90971.32 NOK/day

After decreasing the tax by 40% rate we will calculate the daily net profit.

90971.32 (1-0.4)= 88692.32 NOK

Therefore annual net profit will be :

88692.32$×365= $19423618.08 NOK/year

### Appendix 2

Information for Calculation of GWP.

Our product. 90640 kg CO2/99790.3 kg waste food

2.13 kg CO2 for every kg biogas.

Natural Gas Information for LCA Calculation

Natural Gas Life Cycle CO2 emissions = 75 kg CO2/GJ

Energy Density Natural Gas = 53.6 MJ/kg

GWP = 4.02 kg CO2eq / kg NG