Norwegian University of Life Sciences
Faculty of Environmental Science and Technology
Department of Mathematical Sciences and Technology

Master Thesis 2015
30 credits

Biogas Upgrading: Techno-economic Evaluation of Different Technologies Based on Norwegian Potential of Raw Materials

Henrik Hønsen Huseby

Preface

This master thesis is the result of a master project in biogas at the Norwegian University of Life Sciences, Department of Mathematical Sciences and Technology, in co-operation with Statkraft. The thesis marks the end of my Master of Science degree in Industrial Economics and Technology Management.

I would like to address my deepest gratitude toward my main supervisor Dr. Jorge M. Marchetti and co-supervisor Dr. John Morken for great assistance on the thesis. They have provided me with helpful suggestions and comments in the process of writing the thesis.

Additionally, I would also like to thank Monica Havskjold from Statkraft for introducing me to the topic of biogas upgrading, helping me with the outline of the thesis and sharing of her broad perspectives in useful discussions.

Ås, May 13th 2015

Henrik Hønsen Huseby

Enquiries about this thesis can be sent to henrik_huseby@hotmail.com

Disclaimer

The author does not accept responsibility for any decision taken based on results in this thesis. The models used on both technical and economic evaluations are for research purposes only. For specific applications, please contact the author for recommendations regarding the limitations and scope of the models.

Abstract

This thesis comprises a literature study of the Norwegian potential for biogas production from food waste, fish processing waste and manure, in addition to an evaluation of different technologies for biogas upgrading.

The study shows that the theoretical potential of waste and residues for biogas production is around 6 TWh, of which 2.3 TWh are considered a realistic part of the potential within 2020. This is enough to cover approximately 4% of the total fuel demand associated with the Norwegian transport sector.

To evaluate the technical aspects of biogas upgrading technologies, a multi criteria analysis was used. The basis for this evaluation is data adapted from operating biogas upgrading plants in Norway as well as Europe, in addition to an in-depth literature study. This evaluation shows that for the given sets of criteria, the organic chemical scrubbing technology, often named amine scrubbing, is the best choice.

Furthermore, an economic evaluation was conducted with the purpose of estimating the production cost of amine scrubbing. The results state that the total cost of biogas upgrading is 1.26 NOK/Nm^3 of produced biomethane. The most decisive cost element was electricity and an evaluation of the effect of varying electricity prices was carried out. In addition, an evaluation of the effect of varying natural gas price and cost of raw biogas production was done to provide a broader view of the whole biogas value chain.

Sammendrag

Denne masteroppgaven omfatter et litteraturstudie av potensialet for biogassproduksjon i Norge fra matavfall, fiskeavfall og husdyrgjødsel, i tillegg til en vurdering av ulike teknologier til oppgradering av biogass.

Potensialstudiet viser at det teoretiske potensialet for biogassproduksjon fra avfall og bi-produkter er rundt 6 TWh, hvor anslagsvis 2.3 TWh er regnet som et realistisk potensial innen 2020. Dette er nok til å dekke rundt 4% av det totale drivstofforbruket i Norge.

Det ble brukt en multi-kriterier-analyse for å vurdere tekniske sider av de ulike teknologiene for oppgradering av biogass. Som bakgrunn for vurderingene i analysen, ble data innhentet fra Norske og Europeiske biogassoppgraderingsanlegg, i tillegg til et inngående litteraturstudie. Analysen viser at for de gitte kriteriene så er det organisk-kjemisk skrubbing, også kalt amin skrubbing, som er det beste valget av teknologi.

Videre har det også blitt gjennomført en økonomisk vurdering av amin skrubbing for å estimere produksjonskostnaden for oppgradering av biogass. Resultatene viser at kostnaden ved å oppgradere biogass ligger på om lag 1.26 NOK/Nm^3 produsert biometan. Elektrisitet er den mest avgjørende delen av kostnaden og en vurdering av effekten av varierende elektrisitetspriser ble derfor gjennomført. I tillegg ble det gjennomført en vurdering av effekten av varierende gasspriser og kostnader ved produksjon av rå biogass i den hensikt å skape et bredere bilde av den totale verdikjeden for biogass.

Contents

Abbreviations

$\Delta G°$	Gibbs free energy
AD	Anaerobic digester
BME	Biological methane enrichment
CBG	Compressed biogas
CHP	Combined heat and power
CU	Cryogenic upgrading
EL	Ecological lung
LBG	Liquid biogas
LCFAs	Long chain fatty acids
MNOK	Million Norwegian kroner
MS	Membrane separation
Nm^3	Normal cubic meter
NOK	Norwegian kroner
OCS	Organic chemical scrubber
OPS	Organic physical scrubber
PSA	Pressure swing adsorption
VS	Volatile solids
WM	Wet mass
WS	Water scrubber

List of Figures

List of Tables

1. Introduction

In the face of growing demand for energy, finite reserves of fossil fuels and substantial concerns regarding pollution and greenhouse gas emissions, a new path in the energy sector is essential. Both national and international renewable energy targets have been set, increasing the pressure to utilize wastes and residues in an efficient and sustainable way. The biogas industry represent one of the most important approaches to meet those targets, and are in recent years emerging quite heavily.

The production of biogas transpires through anaerobic digestion of organic materials, both in landfills and reactor facilities. It is rich in methane, but also contains carbon dioxide and small amounts of other impurities. Manure, sewage sludge, food waste, fish processing waste and energy crops can be used to generate biogas. When combusting biogas, energy (heat) are released, and methane is transformed to carbon dioxide. There are several ways to utilize biogas such as heating, electricity production or transport fuel.

The large potential of hydroelectric power in Norway, suggests a use of biogas for transportation purposes. The use of biogas as fuel in vehicles is not prevalent in the Norwegian transport sector yet. However, there may be enhanced interest in the future caused by less access to fossil fuels or due to a transition towards more climate-friendly fuels. The use of biogas in transportation requires cleaning and upgrading of the biogas into fuel quality.

One of the main reasons to favour biogas over fossil fuels is reductions in greenhouse gas emissions. This, and the fact that biogas is made from renewable energy sources, makes it a climate friendly energy carrier. Other benefits from use of biogas rather than diesel are less local air pollution. To show that biogas used as fuel are climate friendly, actual estimations on the reduction of greenhouse gas emissions were done by Swedish Gas Technology Centre. CO_2 life cycle estimations of wet organic material and manure represents a reduction of greenhouse gas emissions of 100 % and 150 %, respectively (Börjesson et al. 2010). This reduction of greenhouse gas emissions is a result of not storing manure or composting wet organic material, and by replacing fossil fuels.

There are a number of steps to be carried out to produce upgraded biogas, also known as biomethane. Possible value chains are presented in Figure 1. Raw materials suitable as substrate for biogas production are the primary part of the value chain. Next are possible pre-treatment and production of raw biogas in small and large plants. The raw biogas can then be cleaned and upgraded and fed into gas grids or used as fuel, or it can be combusted directly for heat or electricity production. The digestate can either be combusted or used as fertilizer. To enhance the final result all the steps should be investigated and improved. This paper, however, mainly addresses the upgrading step of the value chain.

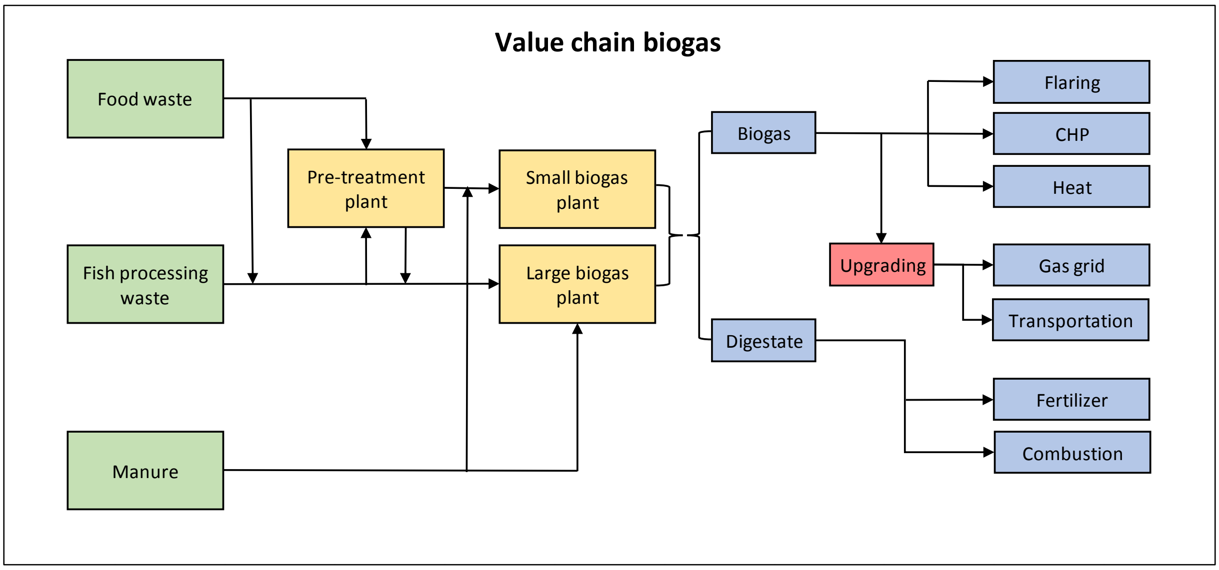

Figure 1: Value chain for biogas production and utilization. This figure is non-exhaustive and lacks logistics. CHP: combined heat and power.

Norway has yet to become a dominating country within the biogas industry, like Sweden and other European countries. This may lay on the abundance and low prices of energy Norway has experienced over the last decades. Even so, there are some biogas development in Norway and 29 biogas plants have been established within 2009 (Nedland & Ohr 2010). 23 of which rely on sewage sludge as substrate, one that combines both sewage sludge and food waste and five food waste plants.

According to Mattilsynet (2015), 15 biogas plants are approved for employing animal by-products as well. At the end of 2014, four biogas plants produced upgraded biogas for transportation and gas grid injection (IEA Bioenergy 2014). One of those plants is located in Romerike and were finished in December 2012. This biogas plant processes food waste, with a capacity of 50,000 tonnes annually, enough to fuel 135 buses (Waste-to-Energy Agency 2014).

The objectives of this thesis are to examine the potential for biogas production in Norway from food waste, fish processing waste and manure and evaluate different methods of upgrading biogas into transport fuel quality. A literature study is conducted with the purpose of presenting an overview of the Norwegian potential for biogas. This framework serves as a basis for the main task of the paper, which is to evaluate different upgrading technologies for biogas. Both technical and economic sides are explored to make a good decision.

2. Literature review

2.1 Potential study

The aim of this Chapter is to present a summary of the previous research that has already been done on the Norwegian potential for biogas. Food waste, fish processing waste and manure are the raw materials to be focused on in this literature review. This is partly because of the unexploited potential the raw materials represent in Norway, and also because they are second-generation substrates.

If not specified, the quantified potentials are theoretical potentials per year, that is, the maximum theoretical energy output of the biogas raw materials. Hence, the accessibility or the production methods applied are not accounted for.

A report from Østfoldforskning and NMBU commissioned by Enova (Raadal et al. 2008), assesses the total Norwegian energy potential of waste and residues to be around 6 TWh. Including the forest resources, the potential will rise to a total of 26 TWh. The realistic potential of forest resources for biogas production is estimated to 4.5 TWh (Fornybar.no 2015). From the theoretical potential of waste and residues only 2.3 TWh are considered as a realistic potential within 2020 (Sletten & Maass 2013). Other sources suggests about 2.22 TWh as the Norwegian potential of raw materials suitable for biogas production (Scarlat et al. 2011; Trømborg 2015).

Of the potentials described, only 0.5 TWh (Sletten & Maass 2013) is utilized today as the total Norwegian biogas production. Potentials and present production are illustrated in Figure 2.

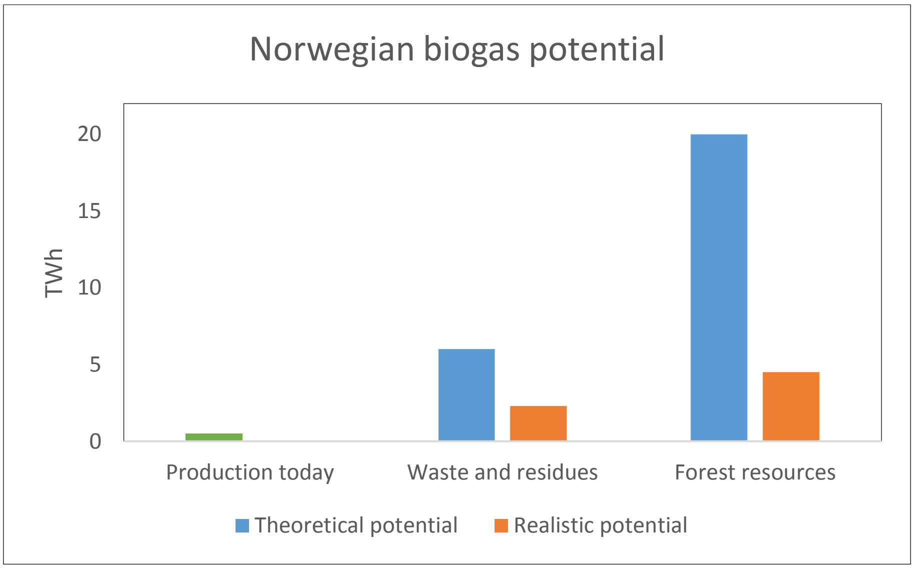

Figure 2: Norwegian biogas production today (TWh), and theoretical and realistic potential of waste and residues and forest resources.

2.1.1 Food waste

This section accumulates the potential for biogas energy from food waste including private households, restaurants/hotels, grocery stores and other food processing industry. Fish processing waste are not considered as food waste in this thesis.

The total energy output from food waste is estimated to be near 1,450 GWh (Raadal et al. 2008). The food waste from private households and grocery stores are calculated from the number of citizens, while food waste potential from restaurants/hotels are calculated from the number of employees. Food waste potential from industry is based on direct numbers from large food industry companies. In a more realistic perspective it is assumed that around 600 GWh could be utilized (Sletten & Maass 2013). This is based on a 2020 perspective and different key figures and fractions for accumulation of food wastes. The potential of food waste are highly correlated with the population pattern, favouring the eastern parts of Norway and the big cities.

2.1.2 Fish processing waste

Fish and fish oil waste as raw material in biogas production are not common in Norway. However, this might change within a few years given the potential of the Norwegian fishing industry. Fish processing waste includes silage, guts and cuttings. The waste products are often high in fat or protein content, and should be used as a co-substrate for biogas production, to avoid inhibition of long chain fatty acids (LCFAs) or ammonia toxification, respectively.

According to Raadal et al. (2008), the energy potential from fish processing waste were estimated to be 640 GWh from a total of 656,000 tonnes of fish waste. From RUBIN (2012), the total of fish waste in 2011 were 816,500 tonnes. Assuming a linear relationship between the mass and energy output, calculations give an energy potential in 2011 close to 800 GWh.

Not all fish processing wastes are optimal for biogas production and huge amounts are currently being utilized as feed in fish farms. This renders the potential drastically and an estimation of the realistic potential is needed. Ward and Løes (2011) suggests an integrated biodiesel and biogas utilization of the remaining realistic potential of Norwegian fish and fish oil waste. From 20,000 tonnes of soapstock, 4,000 tonnes of biodiesel (approximately 51.8 GWh) could be produced. As for biogas, 30,000 tonnes of bleaching earth could produce an extra 1.5 million m^3 of methane, equal to around 16 GWh, when co-digested in biogas plants.

Furthermore, an additional and considerable amount of biogas can be produced using Category 2 wastes. This includes fish waste from manure, waste containing residual veterinary drugs and slaughtered fish not intended for human consumption. Biogas corresponding to 298 GWh can be produced from Norwegian Category 2 fish waste (Ward & Løes 2011).

Sletten and Maass (2013) only consider around 20% of all fish processing waste to be available for biogas production within 2020. This is estimated to 128 GWh.

2.1.3 Manure

Total energy potential from manure were evaluated by Raadal et al. (2008) to be 2,480 GWh. This estimation was conducted based on 2005 numbers for livestock and from SSB (2014c), the number of livestock in Norway has increased by over 37% from 2005 to 2014. Given this, it is expected that the energy potential in 2014 from manure would be close to 3,340 GWh.

There are several other studies conducted on the same potential as well, one or more which has significantly different estimations on the level of energy potential. Mainly the difference relies in compensation for scares farming in Norway, which means it would be inefficient to accumulate manure from all farms. Lindblom and Rasmussen (2008) state that the potential of liquid manure for biogas production is not more than 932 GWh. From Sletten and Maass (2013), the realistic potential within 2020 is 744 GWh. This is based on a 30 % accumulation of all manure available.

The potential from manure is located in a widespread area of Norway. The largest potentials can be found on the south-west coast and the eastern parts of Norway.

The theoretical and realistic biogas potential from food waste, fish processing waste and manure are compared in Figure 3.

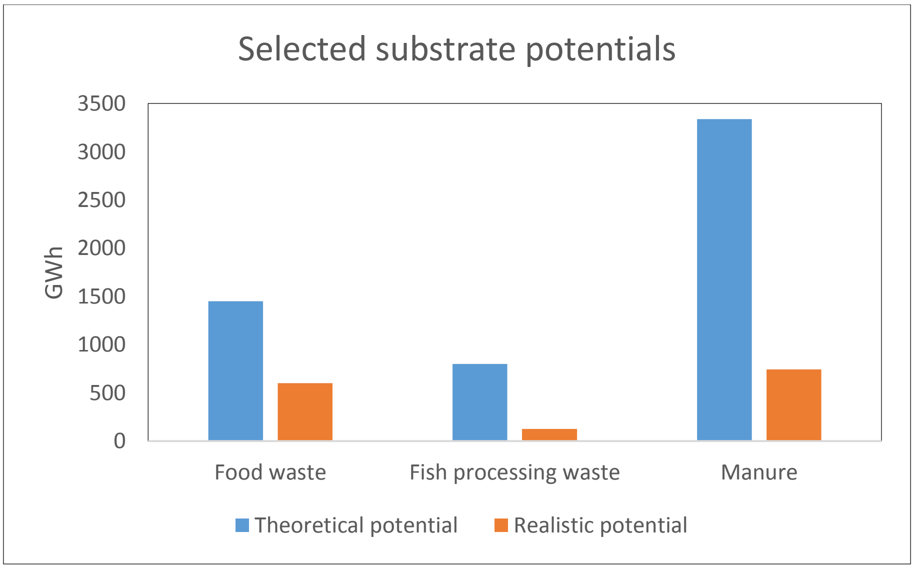

Figure 3: Theoretical and realistic energy potential (GWh) of food waste, fish processing waste and manure.

2.2 Cost of biogas production

This section presents an estimation of the costs of producing biogas from Norwegian raw materials. Two different substrates are evaluated, wet organic waste and manure. Food waste and fish processing waste are categorized as wet organic wastes.

2.2.1 Economics

Production cost in economics is presented as an additional cost to the reference scenario. The production cost based on manure and wet organic waste is evaluated to 1.25 NOK/kWh and 0.54 NOK/kWh, respectively, in addition to the reference cost (Sletten & Maass 2013).

To get a broader vision of the actual costs of developing a more comprehensive biogas production in Norway, it is vital to see what the costs of investing and operating a biogas plant are. Depending on different substrates and number of production plants, the technical costs vary considerable. Sletten and Maass (2013) suggests a possible composition of biogas plants to utilize the Norwegian potential for biogas, divided into the production from manure and the production from wet organic waste.

For the biogas production from manure, there is a demand for 38 industrial facilities (110,000 tonnes) and 55 shared facilities (50,000 tonnes) to treat 3.92 million tonnes of manure, equal to the earlier mentioned potential of 744 GWh. The investment costs of each facility are estimated to 73 million NOK and 42 million NOK, respectively. This adds up to a total of 406 million NOK capital expenditures per year, when assuming 20 years of operating and 5 % interest rate. Operating expenditures are estimated to 561 million NOK per year, including transport, labour, electricity, maintenance and upgrading of the biogas. The cost of upgrading is estimated to 93 million NOK. Total economics then add up to 967 million NOK.

For the biogas production from wet organic waste, the potential of 990 GWh (880 000 tonnes), can be processed in 16 different facilities (55,000 tonnes). Total yearly capital expenditures of the 16 facilities are estimated to 354 million NOK. Including operating expenditures, it adds up to a total economics of 591 million NOK.

2.2.2 Business administration

The production cost in relation to business administration is presented as a surplus or deficit number. The production cost from manure and wet organic waste is evaluated to deficits of 1.27 NOK/kWh and 0.002 NOK/kWh, respectively (Sletten & Maass 2013). This shows that production of biogas with the use of wet organic waste as substrate nearly is viable. Following are the detailed information given by Sletten and Maass (2013).

From biogas production based on manure as substrate, all the revenue comes from selling the biogas. This then adds up to around 240 million NOK yearly, with 0.32 NOK/kWh as the price of gas and the before mentioned production of 744 GWh. The gas price varies, so the estimate must be seen as an example.

Capital expenditures in the business administration sense are based on a higher interest rate (8 %), and makes up a total of 516 million NOK. Total expenses for the production of biogas based on manure then add up to 1.2 billion NOK.

When calculating production of biogas from wet organic waste, revenues include an additional gate-fee. This is estimated to around 700 NOK/tonnes of waste delivered, and thereby a substantial addition to the sale revenues. It can actually represent as much as 2/3 of the total revenues.
Expenses including capital expenses and operating expenses are estimated to around 938 million NOK (0.95 NOK/kWh).

2.3 Law and Regulations

Experience from several EU Member countries have revealed that long term and stable policies, along with strong incentives are needed to build up a biogas market (Scarlat et al. 2011). This section gives an overview of the Norwegian laws and regulations regarding biogas.

Norway has several policy instruments affecting the biogas industry (Klima- og forurensningsdirektoratet 2010), in matter of increased resource access, production and use of biogas. To increase the access to raw materials the most important instruments are landfill ban of wet organic waste and delivery support for manure. Landfill ban means that all wet organic waste has to be delivered to a facility designed for waste treatment, which is allowed to acquire a fee for the waste that is delivered.

In the next part of the value chain, production, investment support for both small and large biogas plants are given. Enova supports projects with energy targets on a minimum of 1 GWh, while Innovasjon Norge focus their investment support on small-scale farm plants (Innovasjon Norge 2015).

To increase the use of biogas in the transport sector, exemption from road taxes will be important as well as investment support for biogas transport infrastructure. Road taxes on gasoline is 0.53 NOK/kWh and for diesel 0.38 NOK/kWh. Transnova investment support is, among others, for research, biogas fuel stations and testing of new vehicles. More details on law and regulations in the Norwegian biogas market can be found in (Sletten & Maass 2013).

2.4 International use

Sweden has focused much of their biogas production for use as fuel for vehicles. They are the leading country in Europe when it comes to biogas in the transport sector. The production sums up to a total of around 1,7 TWh yearly from 264 biogas plants (Biogasportalen.se 2014). The most common substrates for biogas production are private food waste, waste from food processing industry and sewage sludge. 54% of the biogas are upgraded to vehicle fuel quality and the remaining combusted, some of which for electricity or heat production (Sahlin & Paulsson 2014).

This amount of production and use of biogas are partly forced by several policy instruments. Among many, the investment programmes Klimp and LIP are worth mentioning, supporting 200 projects with a total of 650 million SEK. On the consumer side, both central and local instruments, are applied to increase the demand for biogas as fuel. This consists of support for biogas vehicles, tax benefits for firm cars, free parking and permission to line up first in cab lines (Marthinsen 2012).

In Denmark, most of the biogas production is from manure. This is a natural development caused by economic beneficial agriculture conditions. However, in oppose to Sweden, the biogas are mostly used for production of electricity and heat (Marthinsen 2012). Also in Denmark, there are well-established investment support systems for biogas plants. Producers of electricity from biogas can also rely on a fixed price on delivery to the power grid. The support scheme mainly focuses on the use of manure as substrate (Marthinsen 2012).

German biogas production is mainly based on energy crops mixed with manure and is used for electricity production. Producers receive a feed-in tariff dependent on different factors, favouring new and small plants using energy crops as substrate. Upgrading of the biogas and good utilization of heat remains are also awarded (Sletten & Maass 2013).

3. Theory & Methods

3.1 Components and impurities

Raw biogas produced in anaerobic digesters typically contains 50-70 Vol-% methane (CH_4), 30-50 Vol-% carbon dioxide (CO_2) and small amounts of other impurities (Yang et al. 2014). The composition of biogas, both from landfill and anaerobic digestion plants are listed in Table 1. Typical impurities include water vapour (H_2O), nitrogen (N_2), oxygen (O_2), hydrogen sulphide (H_2S), ammonia (NH_3) and siloxanes. The impurities pose unwanted effects to utilization of biogas as fuel and gas grid injection. This is, among others, lower calorific value, corrosion in equipment and piping systems, and other mechanical wear to engines and fuel cells. Another negative effect is unwanted emissions (e.g. sulphuric acid) while combusting biogas (Wellinger et al. 2013).

Table 1: Typical components in biogas from landfills and anaerobic digesters (AD) (Wellinger et al. 2013; Yang et al. 2014).

Compound	Unit	Landfill gas	AD gas
Methane	Vol-%	30-65	50-70
Carbon dioxide	Vol-%	25-47	30-50
Nitrogen	Vol-%	0-17	2-6
Oxygen	Vol-%	0-3	0-5
Hydrogen sulphide	mg/m^3	0-1,000	100-10,000
Ammonia	mg/m^3	0-5	0-100
Siloxanes	mg/m^3	0-50	0-50

3.2 Substrates

3.2.1 Definitions

The term biomass is defined as “material of plants and animals, including their waste and residues” (Twidell & Weir 2006). Biomass is used in a wide range of energy purposes, directly via combustion to produce heat, or by converting it into various biofuels or electricity. Wood, industrial and municipal waste, agricultural crops and residues are examples of biomass and represents a renewable source of energy.

Biomass that is appropriate to be fermented is named “substrate” (Deublein & Steinhauser 2008). Fermentation is the biological process of which the substrate forms into methane. This process goes naturally when biomass decomposes in a humid atmosphere in the absence of air, and is also known as anaerobic digestion (Deublein & Steinhauser 2008).

3.2.2 Categories

In general, there are no limitations of which types of biomass that can be used for biogas production. However, some types of biomass are more suitable than others are. Common biogas substrates are food waste, manure, energy crops, sewage sludge and industrial waste. Fish processing waste are not yet common as biogas substrate, but it has a great potential.

The substrates chosen in this thesis (food waste, fish processing waste and manure) have different compositions and consequently different biogas yield as well as methane concentration in the raw biogas. The biogas yield and methane content of different substrates are shown in Table 2. Numbers can vary between different references.

Table 2: Biogas yield and methane concentration from different substrates (Carlsson & Uldal 2009). VS=Volatile solids, WM=Wet mass.

Substrate	Specific biogas yield (Nm^3/ton VS)	Biogas yield (Nm^3/ton WM)	Methane content (%)
Food waste	921	164	61
Fish waste	1,310	537	71
Manure*	371	24	65

*pig and cattle manure.

3.2.3 Composition and biogas yield

The nutritional composition of the substrate will affect the biogas yield and its content of methane as shown in Table 3. The biogas yield that can be achieved is a result of the mixture of the organic molecules fat, protein and carbohydrates. Both the specific biogas yield and the methane content varies between the various molecules.

Variety in the methane and carbon dioxide fraction is mainly due to the use of different substrates and combinations of them, as well as the fermentation process applied. Substrates that are rich in fat can help improve the methane content of the biogas. Fish processing waste, especially fish oil, are rich in fat and consequently yields a biogas with high methane concentration (Ward & Løes 2011).

Table 3: Biogas yield and methane content of the biogas from different nutrients (Petersson & Wellinger 2009). VS = Volatile solids.

Nutrient	Specific biogas yield (l/kg VS)	Methane content (%)
Fat	1,000-1,250	70-75
Protein	600-700	68-73
Carbohydrate	700-800	50-55

3.3 Fuel quality requirements

To use biogas as fuel, there are some requirements to be fulfilled with regards to the quality of the biogas. The requirements resemble those for gas grid injections, but differ to some extent. This section covers the requirements for fuel purposes. These requirements are not finite or absolute, and vary at some extent between countries.

A high energy content is preferred, when using biogas as fuel. Since carbon dioxide cannot be combusted, it only serves as a deadweight in the biogas. Therefore, by upgrading the biogas to a higher methane fraction, it gives the biogas a higher energy content.

There are different standards used to classify the required fuel quality needed for transportation. Sweden has developed a standard specifically for biogas used as vehicle fuel (Swedish Standards Institute 1999). This regulates methane content, which must be at least 95 Vol-% (Petersson & Wellinger 2009). The standard also regulates the content of hydrogen, sulphide and water.

International Organization for Standardization has made a standard called "Natural gas for use as compressed fuel for vehicles – Part 1: Designation of the quality" (International Organization for Standardization 2006). This standard is also used for upgraded biogas and regulates methane content to a minimum of 96 Vol-% (Deublein & Steinhauser 2008). In addition, it sets limitations for the contents of hydrogen sulphide, total sulphur, carbon dioxide, oxygen, hydrocarbons and water.

Wobbe index is often used as a measurement in gas utilization. This index comprehends the ratio between higher heating value and specific gravity. In Sweden, lower Wobbe index must be no less than 43.9 MJ/Nm^3 for the gas to be utilized as vehicle fuel (Persson et al. 2006).

Most standards does not include requirements regarding methane recovery rate, which is very important for the environmental competitive edge of biogas life cycle. In most applications on the European market today, the upgrading process needs to have a methane recovery above 98% (Bauer et al. 2013).

3.4 Cleaning and upgrading

This section provides an overview of the methods for cleaning and upgrading biogas. Some of them are common and in use today, while a few are in research stage. The reason for cleaning and upgrading biogas is to prevent unwanted effects to the engines and other equipment, and to raise the volumetric energy content, respectively. Different cleaning processes and upgrading processes are schematically illustrated in Figure 4.

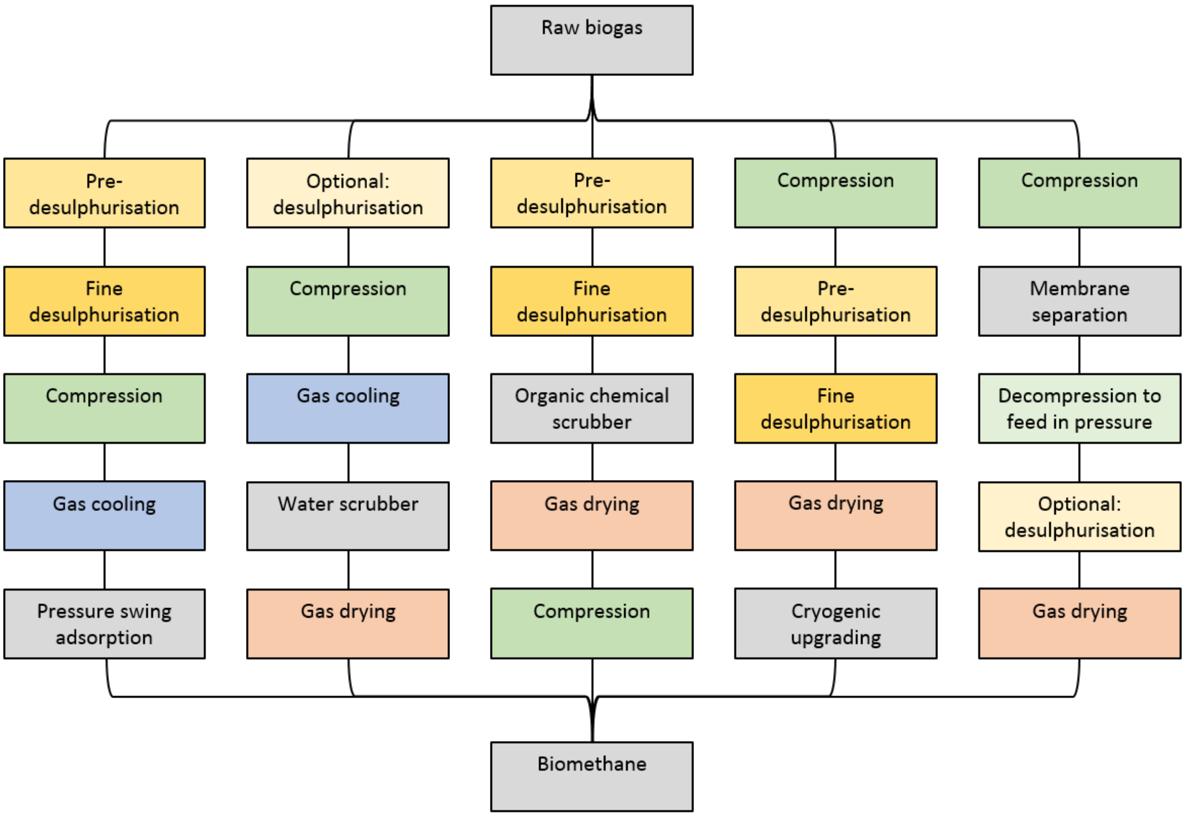

Figure 4: Possible combinations of biogas cleaning processes and upgrading processes (Wellinger et al. 2013).

3.4.1 Definitions

In this thesis, cleaning of biogas is defined as the process in which impurities (undesired gas compounds) in the raw biogas are removed. Upgrading of biogas is defined as the process where carbon dioxide is separated from the biogas. Some upgrading methods both cleans and upgrades biogas, while some methods require a comprehensive pre-cleaning process.

3.4.2 Cleaning technologies

3.4.2.1 Water

Raw biogas is saturated with water, which needs to be removed in order to avoid corrosion in pipelines and other equipment. To remove water from the biogas there are four different methods that can be applied; cooling, compression, absorption and adsorption (Wellinger et al. 2013). Changing the temperature and/or pressure of the biogas in such a manner will affect the solubility of water in the gas and hence the water vapour will condense. Absorption is based on the use of glycol solutions to bind the water (Petersson & Wellinger 2009). The adsorption method can remove water by using e.g aluminium oxide, magnesium oxide, activated carbon, silica or zeolites (Wellinger et al. 2013).

When removing water from the biogas, other impurities dissolved in that water will automatically also be removed. This may include particles and siloxanes and has to be considered when disposing the water (Wellinger et al. 2013).

3.4.2.2 Hydrogen sulphide

Hydrogen sulphide is toxic and corrosive to pipework and other equipment used on utilization of biogas production technologies (Deublein & Steinhauser 2008). It can be removed in the digester itself, after the digester or in combination with the upgrading process (Wellinger et al. 2013). Hydrogen sulphide can have a negative effect on some upgrading methods and thus have to be removed in advance.

Removal of hydrogen sulphide is often divided into three types of methods; biological, physical and chemical. Biological removal lets air into the digester and thereby oxidizes the hydrogen sulphide to elementary sulphur. Too much oxygen will affect the digestion process negatively, and it can also form explosive mixtures between methane and oxygen (Wellinger et al. 2013). Therefore, traces of oxygen are negative if the biogas is to be utilized as vehicle fuel.

Different physical methods can also be used to remove hydrogen sulphide from biogas. Absorption with water or organic solvents are one possibility, and chemical absorption another possibility (Wellinger et al. 2013). Adsorption using activated carbon with defined pore sizes is a rather expensive but efficient method leaving less than 1ppm. (Petersson & Wellinger 2009) of hydrogen sulphide in the gas.

The chemical method for removal of hydrogen sulphide is based on the addition of iron ions into the digester. This produces an almost insoluble iron sulphide which will precipitate in the digester, and is then removed with the digestate (Wellinger et al. 2013).

3.4.2.3 Oxygen and nitrogen

Oxygen and nitrogen are generally not present in biogas since the anaerobic digestion process requires oxygen free atmosphere. However, if for some reason there is air present in the digester, it could leave traces of oxygen and nitrogen in the gas after leaving the digester (Petersson & Wellinger 2009).

Typical methods for removal of oxygen and nitrogen are adsorption using activated carbon, molecular sieves or membranes (Wellinger et al. 2013). They are also removed, in some desulphurisation processes and in some upgrading processes. Oxygen and nitrogen is expensive and difficult to remove, and should be avoided as much as possible when producing biogas.

3.4.2.4 Ammonia

When proteins are degraded, ammonia can be formed. This means that when liquid manure and especially fish processing waste or food industry waste are used as substrates, considerable amounts of ammonia can occur. The pH value and stability of the fermentation process also affect the amount of ammonia produced. High pH value in the digester will increase the formation of ammonia from ammonium, as shown in equation 1 (Deublein & Steinhauser 2008).

$$NH_4^+ \leftrightarrow NH_3 + H^+ \qquad (1)$$

Ammonia is dissolved in water and is usually removed when the gas is dried (Wellinger et al. 2013). Therefore, a separate cleaning step is normally not necessary.

3.4.2.5 Siloxanes

When siloxanes are burned (e.g. in an engine) silicon oxide is formed which can create a problem in gas engines (Deublein & Steinhauser 2008). They can be removed by absorption with organic solvents, strong acids or strong bases, by adsorption with activated charcoal or silica gel, or in a cryogenic process (Ryckebosch et al. 2011). Siloxanes are also removed by some upgrading processes and while separating hydrogen sulphide.

3.4.3 Upgrading technologies

The most developed types of upgrading technologies can be mainly divided into four groups; adsorption, absorption, permeation and cryogenic upgrading. This is illustrated in Figure 5.

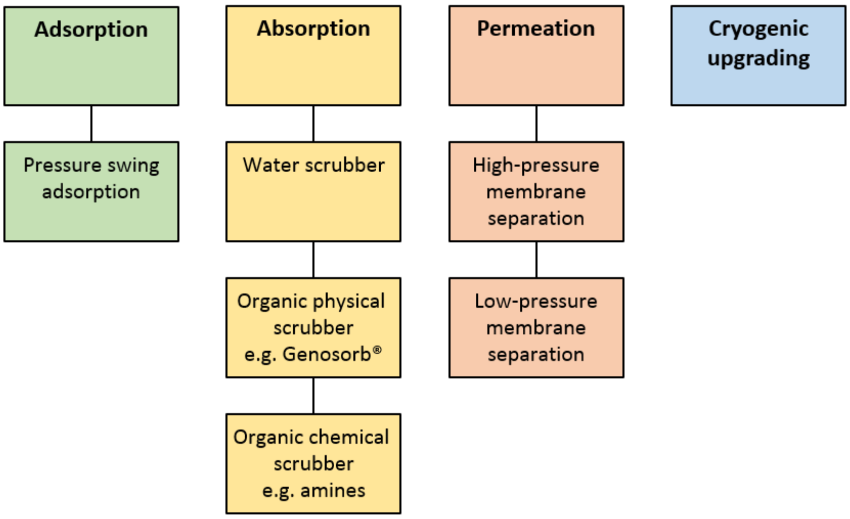

Figure 5: The main groups of biogas upgrading technologies (Wellinger et al. 2013).

3.4.3.1 Pressure swing adsorption (PSA)

The PSA method is an adsorptive biogas upgrading technology, that is, carbon dioxide is separated from the biogas when retained on a surface of a solid at high pressure (Wellinger et al. 2013). The size of the molecular sieves of the adsorbing material traps small molecules like carbon dioxide, oxygen and nitrogen, while bigger molecules like methane passes through. As adsorbing material, usually activated carbon or zeolites are used (Petersson & Wellinger 2009). The adsorbing material is regenerated when pressure is dropped and the adsorbed gas compounds are released. This way a subsequent adsorption cycle is maintained. The PSA process normally includes four steps as shown in Figure 6.

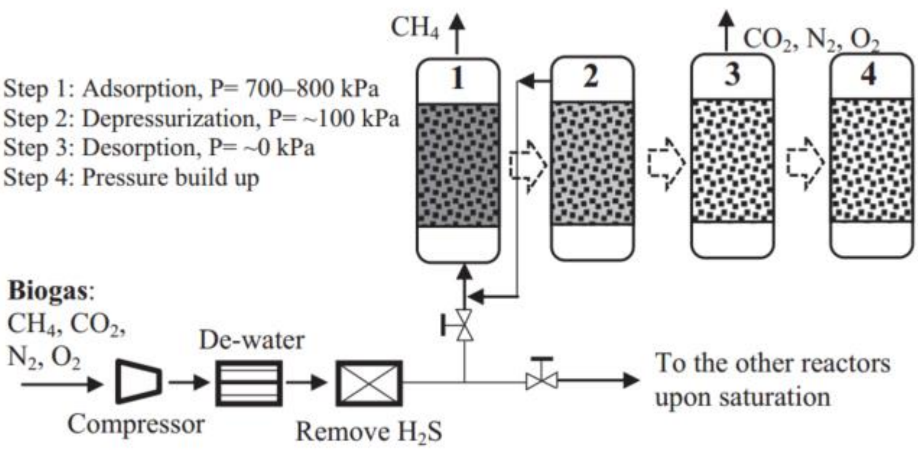

Figure 6: Schematic illustration of PSA process (Yang et al. 2014).

3.4.3.2 Water scrubbing

All absorption methods rely on the principle that carbon dioxide is more soluble than methane. The concept of water scrubbing process is shown in Figure 7. With high pressure in an absorber, raw biogas flows counter-currently into a scrubber tank and meets a flow of water, which is sprayed from the top of the tank. When the raw biogas meets the flow of water in a column, the carbon dioxide will dissolve into the water while methane passes through. The gas leaving the scrubber has a higher concentration of methane.

The water mainly contains carbon dioxide, but also some methane, and is released and transferred back to the raw gas inlet. With low pressure and air blown into a stripper, the water is regenerated (Petersson & Wellinger 2009).

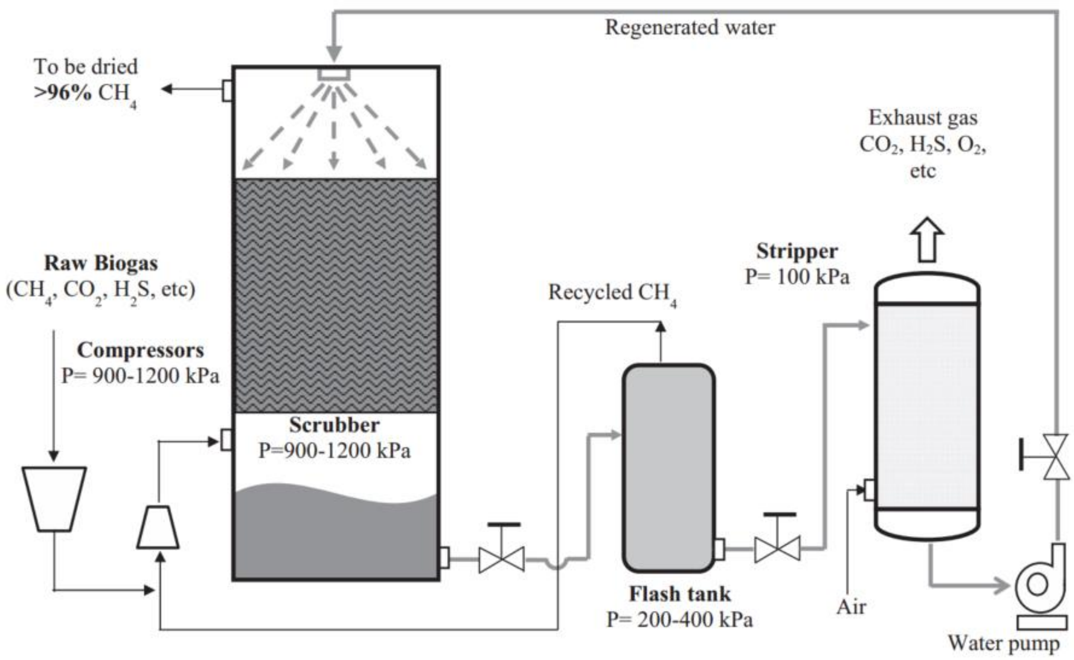

Figure 7: Schematic illustration of water scrubber process (Yang et al. 2014).

3.4.3.3 Organic physical scrubbing

The similarity to water scrubber technology is apparent as the simplified process flow diagram in Figure 8 shows. Organic physical scrubbing differs from water scrubbing with the use of an organic solvent instead of water. This can be polyethylene glycol (e.g. selexol), which carbon dioxide is more soluble in than water. Therefore, the liquid flow can be lower and consequently the upgrading plant can be smaller (Petersson & Wellinger 2009). Used absorbents are regenerated by depressurising and/or heating (Patterson et al. 2011).

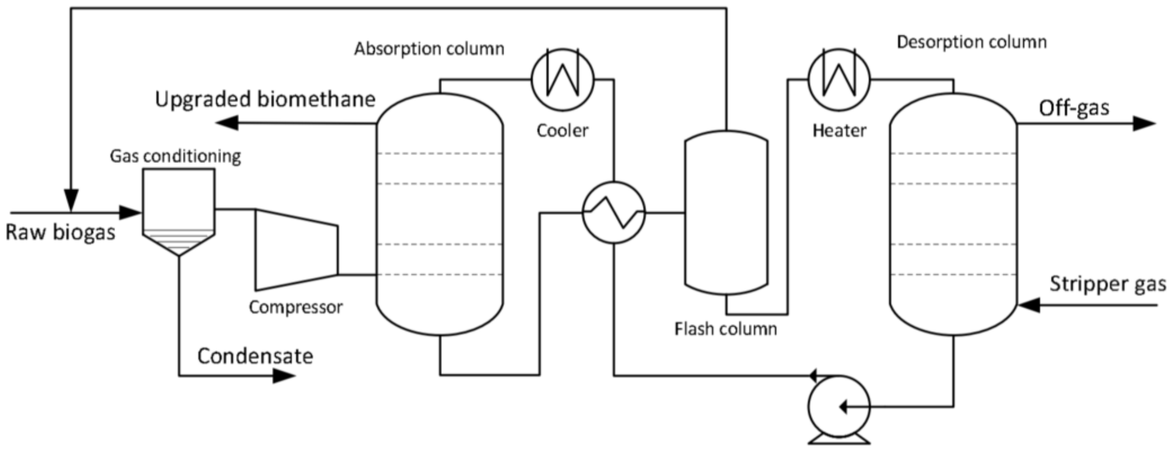

Figure 8: Schematic illustration of organic physical scrubber process (Bauer et al. 2013).

3.4.3.4 Organic chemical scrubbing

Organic chemical scrubbing is conceptually similar to water scrubbing, except that they use amine solutions instead of water. Amine solvent are known for high absorption selectivity of carbon dioxide (Yang et al. 2014). Another difference is that carbon dioxide reacts chemically with the amine, in addition to absorption in the liquid (Petersson & Wellinger 2009). The chemical reaction is strongly selective, making the possible methane loss as low as <0.1% (Petersson & Wellinger 2009).

Unlike the other scrubbing methods, amine scrubbing can proceed at almost atmospheric pressure. Regeneration of the absorption chemical is done by heating it up to a temperature of around 120 °C (Petersson & Wellinger 2009). A possible amine absorption and desorption process is shown in Figure 9.

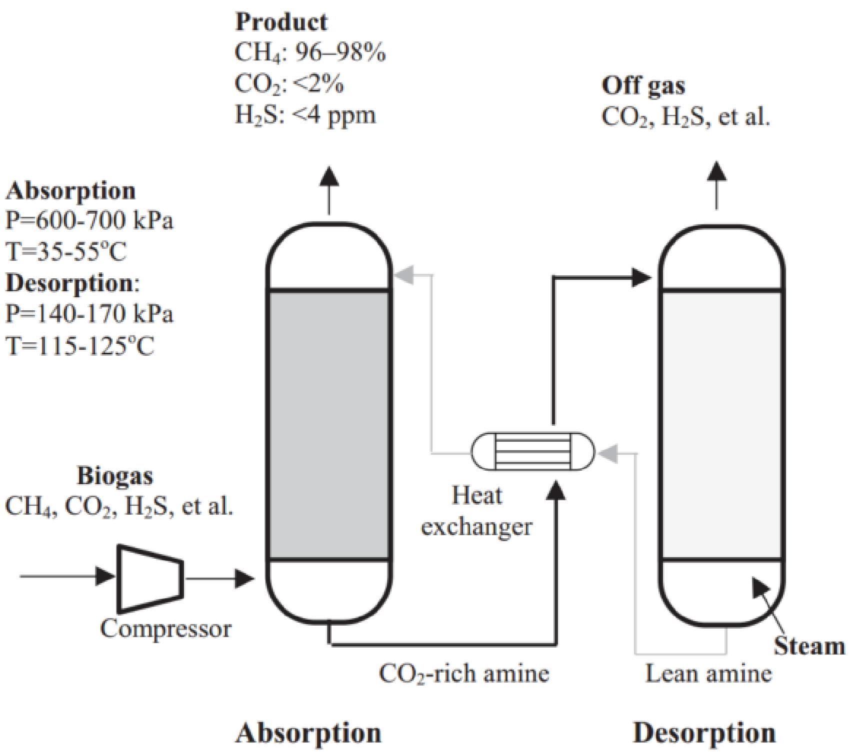

Figure 9: Schematic illustration of organic chemical scrubber process using amines (Yang et al. 2014).

3.4.3.5 Membrane separation

Membrane separation uses polymer membranes that are permeable to carbon dioxide, water and ammonia, while nitrogen and methane mostly do not pass (Petersson & Wellinger 2009). This is shown in Figure 10. Hydrogen sulphide and oxygen permeate through the membrane in different quantities, depending on the membrane material used. Typical membrane materials used are cellulose acetate and aromatic polyimides (Institut für Solare Energieversorgungstechnik 2008). Usually the process where biogas is lead through the membrane is repeated at least once, to separate the gases more.

When comparing different membrane systems, CO_2/CH_4 selectivities, are an essential parameter for economic evaluation of operation (Wellinger et al. 2013). Normal CO_2/CH_4 selectivities are around 50 (Wellinger et al. 2013).

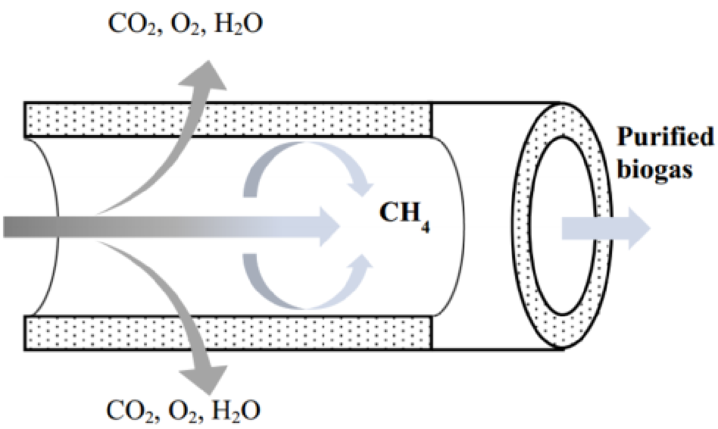

Figure 10: Schematic illustration of membrane separation process (Yang et al. 2014).

3.4.3.6 Cryogenic upgrading

Cryogenic upgrading makes use of the effect of different boiling points of methane and sublimation points of carbon dioxide. The boiling point of methane is -161 °C and the sublimation point of carbon dioxide is -78.5 °C (Chang & Overby 2011). By compressing and cooling down the biogas in steps to which carbon dioxide condenses or sublimates, the liquid or solid fraction of carbon dioxide can be removed. High concentration methane in gas phase can flow separately to a storage tank. Water and siloxanes also condenses in the cooling process and is removed as well (Petersson & Wellinger 2009).

By further cooling processes to make liquid methane, nitrogen can also be removed (Petersson & Wellinger 2009).

3.4.3.7 Biological methane enrichment

This method is based on the use of hydrogen to produce methane from the surplus of carbon dioxide in the biogas. This is possible in the digester itself (in-situ) or in an external processing tank (ex-situ) in addition to the digester. The conversion of hydrogen and carbon dioxide to methane, in the digester, follows the chemical reaction according to equation 2 (Luo et al. 2012).

$$4H_2 + CO_2 = CH_4 + 2H_2O, \quad \Delta G^0 = -130.7\ kJ/mol \tag{2}$$

To bind CO_2 with H_2 and convert them to methane, hydrogenotrophic methanogens is used. This can be extracted from the sludge of anaerobic digesters (Luo & Angelidaki 2012). The method is not yet commercial, but provides a great potential for biogas upgrading, giving the simplicity of the concept. It does not need high pressure or addition of chemicals, as most other upgrading methods, and thereby eliminating many of the costs of upgrading.

3.4.3.8 Ecological lung

Ecological lung is a method using the enzyme carboanhydrase to dissolve carbon dioxide from biogas. The enzyme catalyses the reaction shown in equation 3:

$$H_2O + CO_2 \leftrightarrow H^+ + HCO_3^- \qquad (3)$$

Carboanhydrase is present in our blood where it catalyses the dissolution of carbon dioxide formed during metabolism in our cells. The carbonate is then transported to the lungs, where the same enzyme catalyses the reverse reaction (Petersson & Wellinger 2009).

3.5 Compressed or liquid gas

To use biogas as fuel, the gas needs to be either compressed or liquefied in order to save space in the vehicle and to make transportation of the fuel easier. Liquid biogas (LBG) has much higher energy density than compressed biogas (CBG), with around 3 times the volumetric energy density (Bauer et al. 2013; Yang et al. 2014). However, today CBG is the most common way to utilize biomethane because of its lower production costs (Sletten & Maass 2013). According to Fjeldal et al. (2011), the cost of compressing biomethane to a pressure of 200 bar is approximately 0.6 NOK/Nm^3, and the cost of liquefying around 2 NOK/Nm^3.

3.6 Technical evaluation model

Evaluation of the technical aspects of biogas upgrading is done with the use of a multi criteria analysis, that is, different options are evaluated based on a finite set of criteria. In this analysis, nine different criteria are evaluated for each of the eight upgrading technologies. The criteria are given different weighting, based on the importance regarding biogas upgrading. This is shown in Table 4.

Methane content is the percentage methane in the product gas, also referred to as biomethane. Methane recovery rate is the percentage methane the system is able to recover when subtracting losses in the system and the off-gas. Energy requirements are the necessary energy input, electricity or heat, for a normal upgrading process. The criterion “cleaning process” is evaluation of the need for comprehensive pre-cleaning process or not, for the given upgrading technologies. Materials/chemicals cover the need for water, amines etc. and other extra special input factors. O&M needs are operation and maintenance for the upgrading plants. Plant size/capacity assess the plant footprint and ability to handle different volumes. Controllability is the ability for a plant to change the flow of input raw biogas. The criterion, waste product, judges the upgrading technologies different quality in off-gas and by-products.

The criteria are chosen based on both functional and environmental concerns, but not location specific conditions. Weights are given based on evaluation of the relative importance of the criteria, and considering other literature.

Table 4: The evaluated criteria with their importance and weight.

Criteria	Importance	Weight
Methane content	1	22
Methane recovery	2	18
Energy requirements	3	17
Cleaning process	4	11
Materials/chemicals	5	9
O&M needs	6	7
Plant size/capacity	7	7
Controllability	8	6
Waste product	9	3
		100

After weighting the criteria, the upgrading technologies are given a score (1-9) for each of their criteria, where 9 is best. All the scores are then multiplied with their weight and the total weighted score is given. This result serves as a ground for the technical evaluation.

The scores of the different criteria are based on input and numbers from actual upgrading plants and literature. Average methane content in European upgrading plants are calculated from the IEA Bioenergy database (IEA Bioenergy 2014). Numbers from Norwegian plants are obtained from direct communication with representatives from the upgrading plants (Jørgensen 2015; Tornes 2015).

3.7 Economic evaluation model

The upgrading technology that has the highest score in the technical evaluation is used for the economic evaluation. This evaluation is done based on input numbers from literature and actual Norwegian plants. Numbers for investment cost and capacity are provided by the Frevar KF biogas upgrading plant.

The economic evaluation model estimates costs of upgrading biogas in a medium scale biogas plant. Furthermore, cost of raw biogas production and revenue from sales are added to the model, to calculate a surplus or deficit to the whole value chain. Logistics are not included in the model.

Surplus or deficit, referred to as income in the model, is also presented with varying input factors (electricity price, gas price and cost of raw biogas production).

4. Results

4.1 European upgrading plants

Today, there are well over 300 biogas upgrading plants in Europe, which generate clean biogas for gas grid injection and vehicle fuel purposes (IEA Bioenergy 2014). The selected upgrading technologies in these plants are listed in Table 5, alongside with the number of plants and average methane content in the output gas.

Table 5: Number of plants and average methane content using different upgrading technology in existing biogas upgrading plants in Europe (IEA Bioenergy 2014).

Technology	Plant number	Average methane content (%)*
Water scrubber	115	96.78
Organic chemical scrubber	86	96.83
Pressure swing adsorption	67	96.27
Membrane separation	34	96.33
Organic physical scrubber	18	96.00

*Plants in the Netherlands are excluded from the calculations.

4.2 Norwegian upgrading plants

There are four biogas upgrading plants in Norway which produces biomethane for vehicle fuel or gas grid injection. Those are FREVAR, IVAR, Bekkelaget sewage treatment plant and Romerike biogas plant. The responding plants are listed with their given specifications in the following sections.

4.2.1 Frevar KF

This biogas upgrading plant is located in Fredrikstad and uses sewage sludge and wet organic waste from households and industry as substrate (FREVAR KF 2015). The plant was first operating in 2001, then with a PSA upgrading plant. However, in 2013, the upgrading technology was replaced with a new and larger amine scrubber. Specifications of the plant are listed in Table 6.

Table 6: Selected technical and economic specifications of the FREVAR upgrading plant (Jørgensen 2015).

Technical	
Methane content	97% (+/- 2%)
Methane recovery	~100%
Energy requirements	0,63 – 0,98 kWh/Nm^3 raw gas (steam)
Cleaning process	None (dependent on low H_2S content in raw gas)
Materials and chemicals	Water: 1 m^3/day, Amine: minimal refill
Operation and maintenance	-
Plant size and capacity	600 Nm^3/h (raw gas)
Controllability	0.25 – 100% of nominal load
Waste product	Flaring
Economic	
Capital expenditures	~15 MNOK investment cost
Operating expenditure	-

4.2.2 IVAR IKS

This biogas upgrading plant is located in Mekjarvik near Stavanger. It mainly uses sewage sludge and some wet organic waste as substrate for the raw biogas production (IVAR 2013). The upgrading plant collects sewage sludge from four different rural plants in the region and produces around 30 GWh of biomethane every year (IVAR 2013). The IVAR biogas upgrading plant also uses amine scrubber technology, and consequently the specifications listed in Table 7 resemble the ones of FREVAR upgrading plant.

Table 7: Selected technical and economic specifications of the IVAR upgrading plant (Tornes 2015).

Technical	
Methane content	98-99%
Methane recovery	99.90-99.95%
Energy requirements	El.: 0.15-0.20 kWh/Nm^3 biomethane
	Heat: 0.9-1.2 kWh/Nm^3 biomethane
Cleaning process	None (dependent on low H_2S content in raw gas)
Materials and chemicals	Water: 30-500 m^3/yr
	Amine: (See operating expenditure)
Operation and maintenance	Independent control from certified authority
Plant size and capacity	500 Nm^3/h (raw gas)
Controllability	-
Waste product	Flaring or back-up gas container
Economic	
Capital expenditures	20-30 MNOK investment cost
Operating expenditure:	
- Maintenance	500,000 NOK/yr
- Amine	8,000-45,000 NOK/yr
Total production cost	0.45 NOK/kWh

Furthermore, the plant reports of a composition (by mol-%) of the raw biogas to be around 65% methane, 34% carbon dioxide, 1% nitrogen and traces of hydrogen sulphide. This implies that with a capacity of 500 Nm^3/h of raw gas, the plant produces approximately 325 Nm^3/h of biomethane, neglecting the small losses.

The energy demands are given per Nm^3 of upgraded biogas. The number for heat demand is gross number because some of the heat may be recovered in the system. The heat is used for stripping the amine scrubber.

Before injecting the biomethane into the gas grid, some amount of propane is added to equal the calorific value of natural gas. IVAR IKS is the only plant in Norway doing this.

4.3 Technical evaluation: Multi Criteria Analysis

4.3.1 Options for biogas upgrading

4.3.1.1 Pressure swing adsorption

PSA upgrading plants typically produces biomethane with methane concentration of >96% (Table 5) (Beil et al. 2011; Yang et al. 2014). There is possible to attain increased methane concentrations, but that will significantly lower the methane recovery rates. Usually, methane recovery rates range between 97.5 and 98.5% (Wellinger et al. 2013).

Before the biogas can be upgraded in a PSA plant, hydrogen and water have to be removed. This is to avoid hydrogen from being irreversibly adsorbed on the adsorbing material, and water from destroying the structure of the material (Petersson & Wellinger 2009). Oxygen and nitrogen is partly removed along with the carbon dioxide, in the upgrading process (Yang et al. 2014).

PSA technology can be used on large capacities as well as small-scale biogas plants (Allegue & Hinge 2012; Ryckebosch et al. 2011). This, and its compact technique, makes it a possible choice for many biogas plants. In the pre-cleaning process there is need for chemicals, but the upgrading process does not need additional chemicals (Bauer et al. 2013).

Operating a PSA plant requires low use of energy, estimated to 0.16-0.18 kWh/Nm^3 raw biogas from newer plants (Wellinger et al. 2013). However, operating a PSA plant requires extensive process control and maintenance of malfunctioning valves (Allegue & Hinge 2012; Ryckebosch et al. 2011). The controllability is reportedly 40-100% compared to nominal load (Wellinger et al. 2013).

The off-gas may contain significant amounts of methane, and hence it is necessary to oxidize it in an off-gas treatment step (Wellinger et al. 2013).

4.3.1.2 Water scrubbing

Water scrubber is the most commonly used biogas upgrading method (Table 5). Upgrading plants using water scrubber technology normally produces biomethane with methane concentration of >97% (Ryckebosch et al. 2011). This is close to the average of what actual European plants reports (96.78%) (Table 5). Methane recovery rates range between 98.0 and 99.5% (Ryckebosch et al. 2011; Wellinger et al. 2013).

Water scrubber technology also removes other water soluble impurities like ammonia, dust and to some extent hydrogen sulphide (Yang et al. 2014). Therefore, a separate cleaning procedure is often not necessary. The capacity of the plants is adjustable by changing pressure or temperature (Ryckebosch et al. 2011). The plants may require large footprint.

This upgrading method does not require chemicals in the process. However, there are a high demand of water (Yang et al. 2014). Energy demand for operating a water scrubber plant varies with the size of the plant. Current values for electricity demand is between 0.20 and 0.30 kWh/Nm^3 raw biogas (Wellinger et al. 2013). Operating an water scrubber plant does not require any major process control (Allegue & Hinge 2012; Ryckebosch et al. 2011). Controllability of the biogas flow in the range 40-100% compared to nominal load is possible (Wellinger et al. 2013).

As the recovery rate is not perfect, the off-gas may contain some methane and normally a regenerative thermal oxidation (RTO) is applied to the off-gas (Wellinger et al. 2013).

4.3.1.3 Organic physical scrubbing

According to Institut für Solare Energieversorgungstechnik (2008), physical scrubbers produce biomethane with methane concentration in the range 93-98%. Table 5 shows 96% as the value for methane content. Methane recovery rates range between 96 and 99% (Wellinger et al. 2013).

This technology has the possibility of the parallel absorption of carbon dioxide, hydrogen sulphide and water in the scrubbing column (Wellinger et al. 2013). Consequently, a separate desulphurization is normally not necessary. Furthermore, the physical scrubbers have smaller footprint than water scrubber at the same capacity (Petersson & Wellinger 2009). However, this method uses chemicals (organic reagent).

Electricity demands in new plants varies from 0.23 to 0.27 kWh/Nm^3 raw biogas (Wellinger et al. 2013). In addition, there are a heat demand of 0.10-0.15 kWh/Nm^3 (Wellinger et al. 2013). However, this heat can be provided from the upgrading plant using heat exchangers after compression and/or off-gas treatment.

The plants using this technology are difficult in operation given the complexity of the process. Incomplete regeneration causing reduced operation when dilution of glycol with water is one of the main problems (Ryckebosch et al. 2011). Controllability in the range 50-100% of the nominal load are possible (Wellinger et al. 2013).

The off-gas includes 1-4% methane (Wellinger et al. 2013), making off-gas cleaning necessary. Often, regenerative thermal oxidation is used.

4.3.1.4 Organic chemical scrubbing

Chemical scrubbers, often named amine scrubbers, can produce biomethane with high methane concentration (>99%) (Ryckebosch et al. 2011; Wellinger et al. 2013). The average methane concentration of the European plants are 96.83% (Table 5). Methane recovery rates are stated to be around 99.9% (Petersson & Wellinger 2009; Ryckebosch et al. 2011).

Plants using chemical scrubber technology are advised to remove hydrogen sulphide in advance, because it will otherwise be absorbed in the amine solution and higher temperature will be needed for the regeneration (Petersson & Wellinger 2009).

As the name implies, this method needs expensive chemicals like amine solutions (Petersson & Wellinger 2009). In addition, used chemicals needs to be handled. Given that amines can dissolve significantly more carbon dioxide per unit volume when compared to water, it leads to smaller volumes and plant sizes (Patterson et al. 2011).

There are high total energy demand including low electricity demands (due to low pressure) between 0.06 and 0.17 kWh/Nm^3 raw biogas, but large heat demand between 0.4 and 0.8 kWh/Nm^3 raw biogas (Wellinger et al. 2013). The chemical scrubber process may cause corrosion to the equipment at high temperatures. There are few moving components, making the plant easy to operate (Allegue & Hinge 2012; Ryckebosch et al. 2011). Controllability in the range 50-100% compared to nominal load is possible (Wellinger et al. 2013).

Given the high methane recovery rate, there is normally not required a separate off-gas treatment, other than possible flaring (Wellinger et al. 2013). Besides producing biomethane, this method also produces high quality carbon dioxide (Ryckebosch et al. 2011).

4.3.1.5 Membrane separation

The methane concentration in the biomethane leaving membrane upgrading plants are typically >96% (Table 5) (Ryckebosch et al. 2011), when removing carbon dioxide in several steps. Methane recovery rates range from 85 to 99% (Wellinger et al. 2013).

As mentioned in chapter 3, membranes are permeable to carbon dioxide, water, ammonia and to some extent also hydrogen sulphide and oxygen, but not nitrogen and methane. This means that a separate pre-cleaning process is not required, but it is often applied to get even cleaner biomethane and to prevent membranes from being contaminated.

There are relatively easy to scale up membrane facilities (Yang et al. 2014). The plants have simple construction and high reliability (safety), in addition to easy operation and maintenance (Ryckebosch et al. 2011; Yang et al. 2014). This complies well with the low weight and small footprint of the plants (Allegue & Hinge 2012). No need for chemicals, but membranes can be expensive (Allegue & Hinge 2012). Electricity demands in the range 0.18-0.35 kWh/Nm^3 (Wellinger et al. 2013).

This processes easily adapt to variations in feed composition, flow rate and pressure (Purdue Research Foundation 1996). The off-gas contains significant amounts of methane, and it is necessary to oxidize it in an off-gas treatment step (Wellinger et al. 2013).

4.3.1.6 Cryogenic upgrading

Cryogenic upgrading is often connected to high methane concentrations, but requires huge amounts of energy to reach that methane content. According to Ryckebosch et al. (2011), cryogenic processes typically produce biomethane with methane concentration in the range of 90-98%, depending on the degree of energy use. Methane recovery rates range between 98.0 and 99.9% (Wellinger et al. 2013). When the biogas is upgraded, there is low extra energy demand to reach liquid biogas (LBG).

Before the cryogenic upgrading process there normally is need for a pre-desulphurisation process to reduce hydrogen sulphur (Wellinger et al. 2013). The demand for electricity range from 0.18-0.25 kWh/Nm^3 raw biogas (Wellinger et al. 2013).

Cryogenic upgrading does not need additional chemicals (Yang et al. 2014). This technology produces clean carbon dioxide as a by-product (Ryckebosch et al. 2011). If the off-gas contains significant amounts of methane, off-gas treatment can be necessary (Wellinger et al. 2013).

This is an immature technology with full scale implementation only in recent years, thus there are not sufficient input on O&M, controllability and plant capacity.

4.3.1.7 Biological methane enrichment

Experimental results shows that the methane concentration of the biomethane produced by biological methane enrichment is around 96% (Strevett et al. 1995). If the process is done perfectly, the methane recovery rate can be 100% (Luo & Angelidaki 2013). There are not major energy requirement for this method of biogas upgrading, besides the energy consumed to make hydrogen (Luo & Angelidaki 2012). Hydrogen can alternatively be produced with the surplus electricity from windmills, by electrolyzing water.

Hydrogen sulphide is removed in the process (Ryckebosch et al. 2011), but other impurities needs to be removed in a separate cleaning step if they exceed the limits for vehicle fuel. The method has minimal chemical requirements (Luo & Angelidaki 2012).

When it comes to size of the plant, it depends very much on the concept chosen. An ex situ biogas upgrading plant needs to have an anaerobic reactor with the volume 1/10 of the biogas reactor (Luo & Angelidaki 2012). Another possible concept is to do the upgrading process in situ, which would not require any additional upgrading plant. According to Luo and Angelidaki (2013), the in situ concept has some issues that needs to be solved. One of them is increase of pH to higher than 8.0, which can be solved by co-digestion acidic substrates or pH-control. Second there can be a problem of lower gas-liquid mass transfer rate of hydrogen which can be solved with hollow fibre membrane.

Since this technology is in research stage, there is not evident how much O&M needs the plant would require, as for the controllability and waste product as well.

4.3.1.8 Ecological lung

A research group in Lund, Sweden, showed that biogas can be purified to a methane concentration of 99% (Mattiasson 2005). The technology has theoretically low energy requirements and the plant low O&M needs (CO_2 Solutions 2015). It only uses enzymes, and not expensive chemicals like amines (Petersson & Wellinger 2009).

This technology is in early research stage, and hence there is not any values for recovery rate, plant size/capacity, controllability or waste product, as well as little to no information on possible pre-treatment processes.

4.3.2 Scores

This section summarises the scores given to all the upgrading technologies and their criteria. For some of the upgrading technologies certain criteria is missing sufficient input information, and are therefore not given a score value. The technologies missing one or more criteria score is cryogenic upgrading (CU), biological methane enrichment (BME) and ecological lung (EL). Thus, their total scores are not compared with the other technologies.

In Table 8, scores for all the criteria is listed for each of the eight upgrading technologies based on input from section 4.1, 4.2 and 4.3. It can be seen that in the windows with a line instead of score, the criteria is missing necessary input. Pressure swing adsorption (PSA), water scrubbing (WS), organic physical scrubbing (OPS), organic chemical scrubbing (OCS) and membrane separation (MS) have scores for all of the criteria, and are comparable with regards to total score and total weighted score. The scores adjusted for weight are listed in Table 9.

Table 8: Scores of the criteria and total benefits (red windows indicates highest score within the criterion).

Criteria	Upgrading technologies							
	PSA	WS	OPS	OCS	MS	CU	BME	EL
Methane content	6	7	7	9	6	8	6	9
Methane recovery	5	7	6	9	4	7	9	-
Cleaning process	4	7	8	4	5	3	5	-
Plant size/capacity	8	6	7	8	8	-	-	-
Materials/chemicals	9	5	4	3	5	7	6	8
Energy requirements	8	5	5	3	5	5	8	8
O&M needs	3	5	3	5	8	-	-	8
Controllability	6	6	5	5	7	-	-	-
Waste product	4	6	6	9	4	7	-	-
Total benefits	53	54	51	55	52	37	34	33

Table 9: Weighted scores and total weighted benefits.

Criteria	Upgrading technologies								Weight
	PSA	WS	OPS	OCS	MS	CU	BME	EL	
Methane content	132	154	154	198	132	176	132	198	22
Methane recovery	85	119	102	153	68	119	153	-	17
Cleaning process	44	77	88	44	55	33	55	-	11
Plant size/capacity	56	42	49	56	56	-	-	-	7
Materials/chemicals	81	45	36	27	45	63	54	72	9
Energy requirements	144	90	90	54	90	90	144	144	18
O&M needs	21	35	21	35	56	-	-	56	7
Controllability	36	36	30	30	42	-	-	-	6
Waste product	12	18	18	27	12	21	-	-	3
Total weighted benefits	611	616	588	624	556	502	538	470	100

The highest scoring upgrading technology is organic chemical scrubber (amine scrubber), both for the total benefits and the total weighted benefits. Membrane separation is the lowest scoring upgrading technology in terms of weighted benefits from the five comparable scores. However, organic physical scrubber is the lowest scoring upgrading technology in terms of total benefits.

4.4 Economic evaluation

This section provides an economic evaluation of amine scrubbing for biogas upgrading. The technology is chosen based on the technical evaluation in section 4.3, and are by those criteria the best technical option.

The economic evaluation model is based on interest rate, economic life, electricity price, energy demand, operative days and production. Those key factor numbers are listed in Table 10, and are partly adopted from the FREVAR plant in addition to literature. Assumptions are made regarding interest rate and the economic life of the upgrading plant. If not specified, the resulting cost estimations are referred to Normal cubic meters of biomethane.

Table 10: Overview of key input factors of the economic model (Table 6) (Patterson et al. 2011; SSB 2014a).

Key factors	
Interest rate	5%
Economic life	20 yrs
Electricity price	0.36 NOK/kWh
Energy demand	0.8 kWh/Nm^3 raw gas
Operative days	332 days/yr
Production	600 Nm^3/h (raw gas)
	400 Nm^3/h (biomethane)

Firstly, a study of the cost of upgrading is conducted. Key numbers are listed in Table 11. It shows that the total cost of upgrading biogas with the use of amine scrubber technology is 1.26 NOK/Nm^3 of produced biomethane. Furthermore, a comparison of the cost elements and their fraction of the total upgrading cost are shown in Figure 11.

Input on amortized capital cost is adopted from the FREVAR plant. Admin & support labour are evaluated as a 30% shift, operating labour as one shift and maintenance as 2.5% of investment cost.

Table 11: Economic aspects of the amine scrubbing technology.

Economic aspects	[NOK/yr]
Amortised capital cost	1,203,639
Operating expenditures:	
Electricity	1,376,870
Admin & support labour	300,000
Operating labour	750,000
Maintenance	375,000
Total costs	4,005,509
Specific cost	1.26 NOK/Nm^3

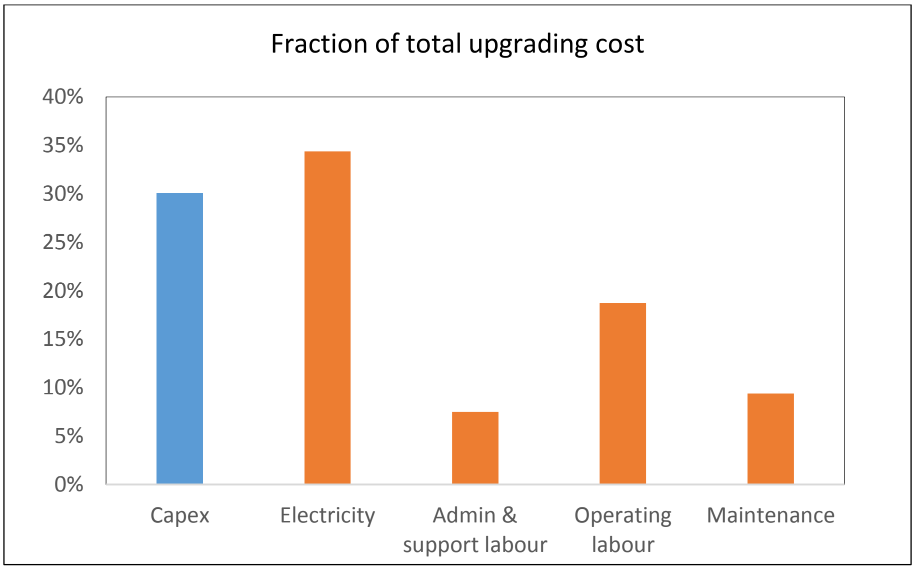

Figure 11: Percentage share of the total cost for the cost elements of upgrading.

Secondly, a study of the viability of the total production is conducted. Cost of raw biogas production from wet organic waste (Chapter 2) is approximately 9.50 NOK/Nm^3 and the natural gas price around 6.69 NOK/Nm^3 (Gasnor 2015). When including these numbers into the economic model, the income (surplus or deficit) can be calculated. It is shown in Figure 12 that within the former mentioned conditions the total biomethane production will result in a deficit of -4.07 NOK/Nm^3.

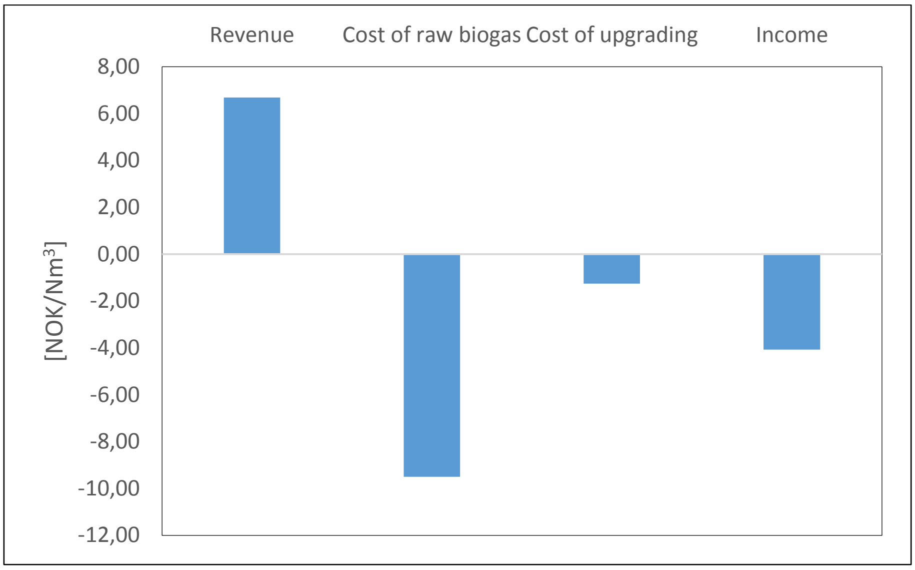

Figure 12: The viability of total biogas production.

Furthermore, varying inputs factors were applied separately to the model in order to investigate the effect on income. From Figure 11, electricity holds more than one third of the total cost of upgrading and is by that very decisive for the upgrading cost. An evaluation of the effect of varying electricity prices on cost of upgrading and income was therefore conducted (Figure 13). It shows that a halving of the electricity price leads to a 17.5% decrease in cost of upgrading. Income is negative for the whole interval.

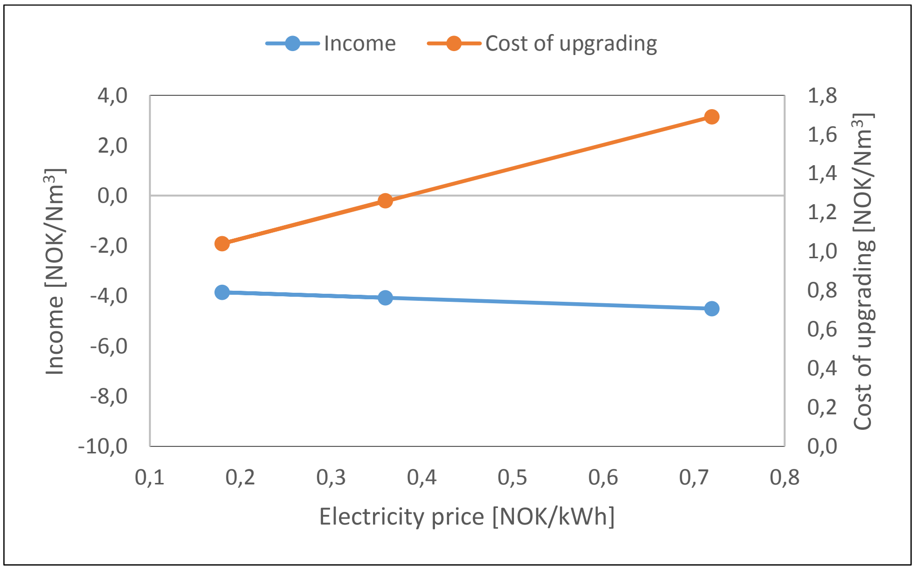

Figure 13: Effect of varying electricity prices on income (1. axis) and cost of upgrading (2. axis).

Varying gas prices was then included in the model to evaluate its effect on income. It is shown in Figure 14 that for a doubling in gas prices, income is positive at 2.62 NOK/Nm^3. Break-even are at a gas price of 10.76 NOK/Nm^3.

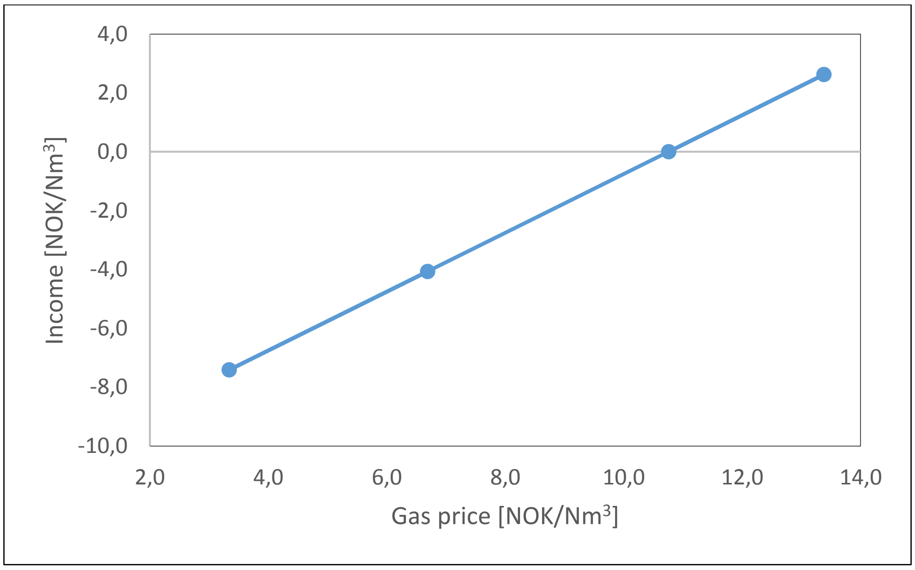

Figure 14: Effect of varying gas prices on income.

Lastly, varying cost of raw biogas production was implemented into the model. This can be seen in Figure 15. It shows that a production cost of raw biogas at 5.34 NOK/Nm^3 gives break-even. A halving of the production cost a positive income of 0.68 NOK/Nm^3 is reached.

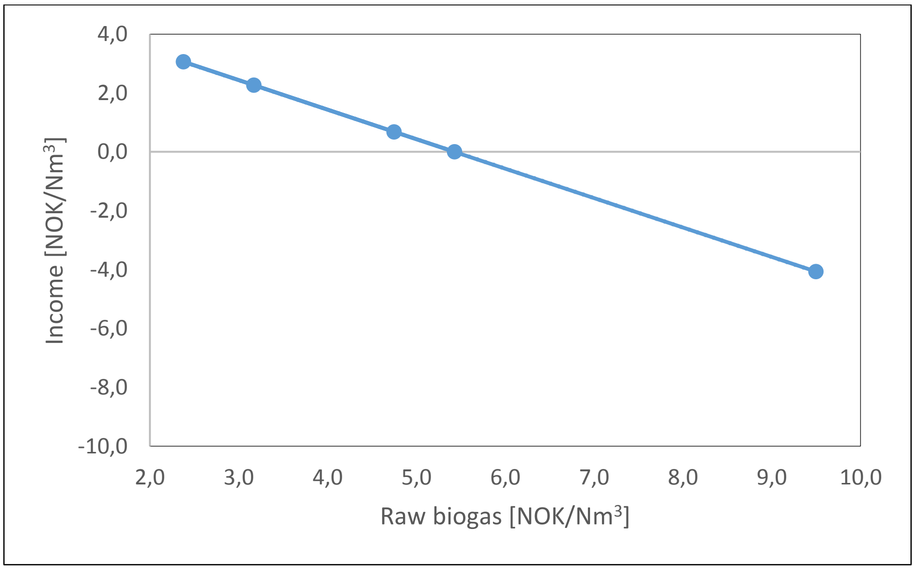

Figure 15: Effect of varying cost of raw biogas production on income.

5. Discussion

The main objective of this thesis was to evaluate different methods of upgrading biogas into transport fuel quality. Input from Norwegian and European plants, in addition to an in-depth literature study resulted in a multi criteria analysis that quantified the different upgrading technologies.

European upgrading plants use a variety of different upgrading technologies, including pressure swing adsorption, water scrubber, organic physical scrubber, organic chemical scrubber and membrane separation. This is interesting because it might be assumed that one technology would be favoured in the market. But instead, the choice of technology are relatively spread. This may come from different preferences in countries, accompanied with quite diverse technical performance of the different upgrading technologies.

The average methane content of European upgrading plants for each technology (Table 5), only range from 96.00 to 96.83%. This may be a result of the fuel standards described in section 3.3, and are possibly not the best way of interpreting the potential of these technologies. In other words, if there is a requirement of e.g. 96% methane content in the biomethane, often there is not any incentives for further purification. This makes some numbers in literature a bit different from numbers in actual plants. Another way of looking at it is that actually all of the listed upgrading technologies in Europe satisfy the demands for methane content. However, that can be a result of different setup strategies (e.g. rendering the methane recovery) which has to be taken into account.

As for the Norwegian plants, the inputs are quite similar to each other and to the literature. Methane content is within expected values, noteworthy is the fact that both plants reports of some variation. This may lay on varying contents in the raw biogas, as well as variation in the biogas flow. Methane recovery rates for both plants are also very compliant with literature. The same goes for the controllability and waste product as well. Energy demand is in the higher range of other literature. An interesting observation, however, is that both plants does not have any pre-cleaning process as suggested in most literature. This can indicate that Norwegian plants choose higher energy consumption before an extra treatment process.

The scores in the multi criteria analysis shows that the organic chemical scrubbing are the highest scoring technology for both total benefits and total weighted benefits. The scores for total benefits are very close, indicating that different weighting of the criteria will have significant impact on the outcome. It is possible that some buyers of upgrading plants will prioritise otherwise than the given weighting in this thesis, and thereby resulting in different outcome.

Organic chemical scrubbing have four highest scoring criteria, including methane content, methane recovery, plant size/capacity and waste product. However, this technology also has three lowest scoring criteria implying a varying technology. In contrast, the water scrubbing technology does not have any highest scoring criteria (and only one lowest scoring criteria), but lines up second in both total benefits and total weighted benefits. The evenness is probably one of the main reasons that water scrubber plants have become the most common technology in Europe.

The three technologies excluded from the total score comparison, all have features that can lead to a promising future. The cryogenic upgrading is still in early stage full scale testing. The big drawback is probably the large demand for energy and need for comprehensive pre-cleaning, in addition to an immature technology. However, if the biomethane is to be liquefied anyways (as a way of transporting the fuel), the technology may have a bright future. Biological methane enrichment has two highest scoring criteria, including methane recovery and energy demand. This technology actually produces more methane than the raw gas contains, by input of hydrogen. A possible application of this technology is in combination with windmills that produce hydrogen from surplus electricity. Ecological lung also shows good potential with highest scoring criteria in both methane content and energy demand.

The results from the economic evaluation of the amine scrubbing technology are based on a set of input parameters and assumptions. Amortized capital cost is evaluated from the FREVAR investment estimate and an interest rate of 5%. This interest rate may be too low in a business administration perspective, where investors might demand more return on their capital investment. However, it gives a good view on today's situation with very low interest rates in the entire European region. The energy demand is also adapted from the FREVAR plant, using the average value of operation. This value varies to some extent in the literature, and may be seen as a small uncertainty.

The total production cost of 1.26 NOK/Nm^3 is comparable to other studies on biogas upgrading. According to Wellinger et al. (2013), the specific upgrading costs of amine scrubbing equals from 0.94 to 1.32 NOK/Nm^3, when considering a capacity of 500 Nm^3/h (raw gas). For a capacity of 1000 Nm^3/h (raw gas), the interval is 0.77-1.11 NOK/Nm^3. It is clear from literature that there is a significant economy of scale associated with biogas upgrading, favouring large plants.

The total production cost of biogas upgrading include capital expenditures, electricity, labour and maintenance. Cost of compressing or liquefying and distribution of the biomethane are not included in the cost evaluation. Capital expenditures represent close to one third of the total production cost. Hence, biogas upgrading is a capital demanding industry. Electricity prices represent just over one third of the total production cost. Given that electricity prices vary between seasons and years, an evaluation of the effect of varying electricity prices was done. Low Norwegian electricity prices can to some extent then contribute to viability of biogas upgrading.

The viability of biogas upgrading also depends significantly on the sales price of natural gas, being that biomethane could be a substitute. Additionally, raw biogas production is an important factor to consider in the big picture. Improvements of technology in the raw biogas production, can contribute to a cheaper line of cost for the whole biogas value chain.

Another way of approaching the viability of biomethane production is the use of political instruments. Some sort of support scheme or taxation of competitive products could lead to a greater development in the biogas industry. Direct production subsidy is one of the most obvious ways to increase the revenues and could be considered in combination with investment support in an early stage of a biogas market establishment. On the other side, taxation of substitutes would also serve as beneficial for competitiveness of biomethane. The use of such instruments need to be evaluated and compared with the climate-profit from biomethane.

The secondary objective of this thesis was to examine the potential for biogas production in Norway from food waste, fish processing waste and manure. This study states that around 1.5 TWh are a realistic potential for biogas production from those substrates. Including other Norwegian waste and residues, 2.3 TWh is the total realistic potential for biogas production in Norway. This total could fuel close to 10,000 buses or cover approximately 4% of the total fuel demand associated with the Norwegian transport sector (SSB 2014b). This suggests that the focus on biogas as fuel should be directed at parts of the transport sector, that being e.g. fleet vehicles like buses, ships, and trucks.

All the substrates that represent the total Norwegian potential for biogas production can be upgraded and used as fuel. It is hard to argue that one or another of the upgrading technologies is more suitable for a certain substrate. The joint preference for all of the upgrading technologies is that the higher methane content in the raw gas, the easier the upgrading process goes.

6. Concluding remarks

Biogas upgrading is a promising and developing industry in Europe with great potential of contributing to meet the growing demand for energy, finite reserves of fossil fuels and substantial concerns regarding pollution and greenhouse gas emissions.

In Norway, the realistic potential of waste and residues for biogas production is around 2.3 TWh. This is only enough to cover approximately 4% of the total fuel demand associated with the Norwegian transport sector. Hence, some parts of the transport sector should be prioritised as the focus for biogas as fuel. This can be fleet vehicles like buses, ships and trucks.

The technical evaluation of biogas upgrading technologies favour the organic chemical scrubbing (amine scrubbing) technology, with water scrubbing and PSA in the following ranks. However, it is vital to understand that the evaluation is done on a location neutral basis, which means that no concern is made regarding local conditions like access for e.g. water, amines etc. This is of course important factors to include in the decision of upgrading technology.

The cost evaluation of amine scrubbing technology states that the cost of biogas upgrading is 1.26 NOK/Nm^3 of produced biomethane . This is only viable with lower cost of raw biogas production, higher natural gas prices or some sort of support scheme.

7. Future work

Potentials:

Study other potential raw materials like algae, sewage sludge from fish farming and cellulose rich substrates.

Biogas upgrading:

Distribution of biogas, compressed or liquid.

Necessary changes in the vehicle fleet and possible problems and dangers with gas vehicles.

8. References

Allegue, L. B. & Hinge, J. (2012). Biogas and bio-syngas upgrading: Danish Technological Institute.

Bauer, F., Hulteberg, C., Persson, T. & Tamm, D. (2013). Biogas upgrading - Review of commercial technologies. Malmö, Sweden: Svenskt Gastekniskt Center.

Beil, M., Heetkamp, J., Klaas, U., Pott, J., Rossol, D., Schäfer, A., Sprick, A. & Wöffen, B. (2011). DWA-Regelwerk: Merkblatt DWA-M 361 Aufbereitung von Biogas: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfalle e. V., Hennef.

Biogasportalen.se. (2014). *Biogas i siffror*. Available at: http://biogasportalen.se/BiogasISverigeOchVarlden/BiogasISiffror (accessed: 02.03.2015).

Börjesson, P., Tufvesson, L. & Lantz, M. (2010). Livscykelanalys av svenska biodrivmedel: Svenskt Gastekniskt Center.

Carlsson, M. & Uldal, M. (2009). Substrathandbok för biogasproduktion: Svenskt Gastekniskt Center.

Chang, R. & Overby, J. (2011). *General Chemistry. The Essential Concepts*. Sixth ed. New York: McGraw-Hill.

CO_2 Solutions. (2015). *Technology Benefits*. Available at: http://www.co2solutions.com/en/benefits (accessed: 06.04.2015).

Deublein, D. & Steinhauser, A. (2008). *Biogas from Waste and Renewable Resources. An Introduction*. Weinheim: WILEY-VCH Verlag GmbH & Co. KGaA.

Fjeldal, P., Økstad, E., Leffertstra, H. & Lindegaard, A. (2011). Biogass fra sambehandling av husdyrgjødsel og våtorganisk avfall - Kostnader og reduksjon av klimagassutslipp gjennom verdikjeden. Oslo: Klima- og forurensningsdirektoratet. 58 pp.

Fornybar.no. (2015). *Tilgang på bioenergi*. Available at: http://www.fornybar.no/bioenergi/ressursgrunnlag (accessed: 28.04.2015).

FREVAR KF. (2015). *Biogass - tekniske data*. Available at: http://www.frevar.no/vare-anlegg/biogass/biogass---tekniske-data/ (accessed: 17.04.2015).

Gasnor. (2015). *Priser/betingelser*. Available at: http://gasnor.no/bolig/priserbetingelser/ (accessed: 25.04.2015).

IEA Bioenergy. (2014). *Up-grading Plant List*. Available at: http://www.iea-biogas.net/plant-list.html (accessed: 05.03.2015).

Innovasjon Norge. (2015). *Bioenergiprogrammet - biovarme/-gass og flisproduksjonsutstyr*. Available at: http://www.innovasjonnorge.no/no/finansiering/bioenergiprogrammet/#.VP7l2fmG-ao (accessed: 10.03.2015).

Institut für Solare Energieversorgungstechnik. (2008). Biogas Upgrading to Biomethane.

International Organization for Standardization. (2006). *ISO 15403-1 Natural gas -- Natural gas for use as a compressed fuel for vehicles -- Part 1: Designation of the quality*.

IVAR. (2013). *Biogass*. Available at: http://www.ivar.no/biogass/category701.html (accessed: 24.04.2015).

Jørgensen, R. (2015). *(Personal Communication)*.

Klima- og forurensningsdirektoratet. (2010). Klimakur 2020. Tiltak og virkemidler for å nå norske klimamål mot 2020. Oslo. 312 pp.

Lindblom, P. G. & Rasmussen, R. O. (2008). Bioenergy and Regional Development in the Nordic Countries: Nordregio. 96 pp.

Luo, G. & Angelidaki, I. (2012). Integrated Biogas Upgrading and Hydrogen Utilization in an Anaerobic Reactor Containing Enriched Hydrogenotrophic Methanogenic Culture. *Biotechnology and Bioengineering*, 109 (11).

Luo, G., Johansson, S., Boe, K., Xie, L., Zhou, Q. & Angelidaki, I. (2012). Simultaneous Hydrogen Utilization and In Situ Biogas Upgrading in an Anaerobic Reactor. *Biotechnology and Bioengineering*, 109 (4).

Luo, G. & Angelidaki, I. (2013). Innovative methods for biogas upgrading by the addition of hydrogen to anaerobic reactor: Technical University of Denmark.

Marthinsen, J. (2012). Økt utnyttelse av ressursene i våtorganisk avfall. Oslo: Mapex. 110 pp.

Mattiasson, B. (2005). Ekologisk lunga för biogasuppgradering: Nationellt Samverkansprojekt Biogas i Fordon.

Mattilsynet. (2015). *Official list of lists of approved and registered plants and operators handling animal by-products*. Available at: http://www.mattilsynet.no/om_mattilsynet/godkjente_produkter_og_virksomheter/?kategori=1002&liste=10102#godkjenninger (accessed: 05.03.2015).

Nedland, K. T. & Ohr, K. (2010). Utvikling av biogass i Norge, Forprosjekt: Avfall Norge.

Patterson, T., Esteves, S., Dinsdale, R. & Guwy, A. (2011). An evaluation of the policy and techno-economic factors affecting the potential for biogas upgrading for transport fuel use in the UK. *Energy Policy*, 39: 1806-1816.

Persson, M., Jönsson, O. & Wellinger, A. (2006). Biogas Upgrading to Vehicle Fuel Standards and Grid Injection: IEA Bioenergy.

Petersson, A. & Wellinger, A. (2009). Biogas upgrading technologies - developments and innovations: IEA Bioenergy.

Purdue Research Foundation. (1996). *Proceedings of the 50th Industrial Waste Conference May 8, 9, 10, 1995*. Purdue University, West Lafayette, Indiana: CRC Press.

Raadal, H. L., Schakenda, V. & Morken, J. (2008). Potensialstudie for biogass i Norge, OR 21.08: Østfoldforskning & NMBU. 55 pp.

RUBIN. (2012). *Varestrømanalyse for 2011*: Stiftelsen RUBIN. Available at: http://www.rubin.no/images/files/documents/varestrm_2011_nettversjon1.pdf (accessed: 11.02.2015).

Ryckebosch, E., Drouillon, M. & Vervaeren, H. (2011). Techniques for transformation of biogas to biomethane. *Biomass and Bioenergy*, 35 (5): 13.

Sahlin, K. & Paulsson, J. (2014). Production och användning av biogas och rötrester år 2013. Eskilstuna, Sweden: Energimyndigheten & Energigas Sverige.

Scarlat, N., Dallemand, J.-F., Skjelhaugen, O. J., Asplund, D. & Nesheim, L. (2011). An overview of the biomass resource potential of Norway for bioenergy use. *Renewable and Sustainable Energy Reviews*, 15 (7): 3388-3398.

Sletten, T. M. & Maass, C. (2013). Underlagsmateriale til tverrsektoriell biogass-strategi. Oslo: Klima- og forurensningsdirektoratet. 245 pp.

SSB. (2014a). *Electricity prices, Q4 2014*. Available at: https://www.ssb.no/en/energi-og-industri/statistikker/elkraftpris/kvartal/2015-02-25 (accessed: 25.04.2015).

SSB. (2014b). *Energiregnskap og energibalanse, 2012-2013*. Available at: http://www.ssb.no/energi-og-industri/statistikker/energiregn/aar/2014-11-05?fane=tabell&sort=nummer&tabell=203572 (accessed: 30.04.2015).

SSB. (2014c). *Strukturen i jordbruket, 2014, førebelse tal*: SSB. Available at: http://www.ssb.no/a/nos/ (accessed: 11.02.2015).

Strevett, K. A., Vieth, R. F. & Grasso, D. (1995). Chemo-autotrophic biogas purification for methane enrichment: mechanism and kinetics. *The Chemical Engineering Journal and The Biochemical Engineering Journal*, 58 (1): 71-79.

Swedish Standards Institute. (1999). *SS 15 5438 Motorbränslen - Biogas som bränsle till snabbgående ottomotorer (motor fuels - biogas as fuel for high-speed ottoengines)*. Stockholm, Sweden.

Tornes, O. (2015). *(Personal Communication)*.

Trømborg, E. (2015). IEA Bioenergy task 40 - Country report 2013 for Norway.

Twidell, J. & Weir, T. (2006). *Renewable Energy Resources*. 2. ed.: Taylor & Francis.

Ward, A. J. & Løes, A.-K. (2011). The potential of fish and fish oil waste for bioenergy generation: Norway and beyond. *Biofuels*, 2 (4): 375-387.

Waste-to-Energy Agency. (2014). Annual and environmental report 2013. City of Oslo.

Wellinger, A., Murphy, J. & Baxter, D. (2013). *The biogas handbook: Science, production and applications*. Woodhead Publishing Series in Energy: Woodhead Publishing Limited.

Yang, L., Ge, X., Wan, C., Yu, F. & Li, Y. (2014). Progress and perspectives in converting biogas to transportation fuels. *Renewable and Sustainable Energy Reviews*, 40.

Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no