Master's Thesis

A techno-economic comparison of biogas upgrading technologies in Europe

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ABSTRACT

Biogas can be cleaned and upgraded to be used as a vehicle fuel, injection into the gas grid, heat and power generation. The carbon dioxide removed from the process can be used be utilized by industry. The main biogas upgrading technologies in Europe are Pressure Swing Adsorption and Water Scrubbing. The first objective is to compare the economics of small, medium and large scale biogas upgrading plants in Europe. The second objective is to evaluate the technical feasibility of small scale biogas upgrading in Europe. This study used a self-designed questionnaire which is sent to biogas plant owners/operators. The questionnaire aims to assess the technical issues, process conditions, biogas production, the upgrading system, energy use and economics. It also included an in-depth literature review.

It was evaluated that the economies of scale favour larger biogas plants where the desired scale should be between 500 and 1,400 Nm^3/hour of raw biogas. It is also not economically feasible for biogas plant smaller than 150 Nm^3/hour to injection into the grid or for commercial fuel stations. However, small scale biogas upgrading can be used to locally within small communities to heat, electric and vehicle farm which could be for example used on farm scale locations. The economics for smaller plants had much higher specific costs that the larger biogas upgrading plants. The economies of scale therefore, show that the larger plants are favoured for producing higher quality gas, lower methane loses, higher plant efficiency and higher profitability. The profit per Nm^3 of upgraded biogas should be around 0.35-0.45 € to achiever the payback time of 5 years with small scale plants. This means that the cost price for biogas upgrading for small scale plants should be less than 0.20-0.30 €/ Nm^3.

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TIIVISTELMÄ

Biokaasua voidaan hyödyntää lämmön- ja energiantuotannon polttoaineena tai puhdistaa ja jalostaa käytettäväksi esimerkiksi ajoneuvojen polttoaineena . Prosessissa vapautuvaa hiilidioksidia voidaan hyödyntää teollisuudessa. Euroopassa käytettävät pääasialliset biokaasun jalostustekniikat ovat PSA (Pressure Swing Adsorption) sekä vesipesu (Water Scrubbing). Tämän työn ensimmäinen tavoite on vertailla pienten, keskisuurten sekä suurten biokaasun jalostuslaitosten taloudellisuutta Euroopassa. Toinen tavoite on arvioida pienten biokaasulaitosten teknisiä mahdollisuuksia Euroopassa. Tutkimusmenetelmänä on käytetty kyselylomaketta, joka on lähetetty biokaasulaitosten omistajille/operoijille. Kyselyn tarkoituksena on selvittää biokaasulaitosten teknisiä kysymyksiä, prosesseja, energian käyttöä sekä taloudellisuutta. Aiheeseen syvennytään myös kirjallisuuden kautta. Taloudellisin kokoluokka biokaasulaitokselle on välillä 500 ja 1400 Nm^3 raakaa biokaasua tunnissa tuottava laitos. Pienien biokaasulaitosten (alle 150 Nm^3/h) ei kannata siirtää biokaasua kaasuverkkoon tai kaupallisille polttoaineasemille. Toisaalta pieniä biokaasulaitoksia voidaan hyödyntää paikallisesti pienissä yhteisöissä tuottamaan lämpöä ja sähköä sekä käyttövoimaksi maatalouskoneille. Mukaan pienillä biokaasulaitoksilla on suuremmat yksikkökustannukset kuin suuremmilla laitoksilla. Suurempia biokaasulaitoksia käyttämällä päästäänkin korkeampaan kannattavuuteen.

Contents

ABBREVIATIONS

AD	Anaerobic Digestion
AEBIOM	European Biomass Association
CHP	Combined Heat and Power
EU	European Union
GHG	Greenhouse Gases
HRT	Hydraulic Retention Time
Mtoe	Mega tonne
kWh	Kilowatt hours
Nm^3/h	Normal Metres Cubed per Hour
OLR	Organic Loading Rate
PSA	Pressure Swing Adsorption
PCDD	Polychlorinated Dibenzo-Para-Dioxins
PCDF	Polychlorinated Dibenzo-Furans
t	Metric Tonne
TS	Total Solids
VS	Volatile Solids
€/kWh	Euros per Kilowatt Hour
€/y	Euros per Year
%	Percent

1 INTRODUCTION

Biogas production is a process which uses anaerobic conditions together with micro-organisms and organic substrates in order to produce a mixture of gases; mainly carbon dioxide and bio-methane. Organic substrates that can be used as a feedstock are energy crops, manures, industrial wastes, sewage sludge, and the organic fraction of municipal solid wastes. Biogas is produced naturally via many processes such as rice paddies, marshes and ruminants. Biogas can also be produced in engineered systems such as; anaerobic digestion, sewage plants and landfills. Table 1 shows the composition of the raw biogas including the average percentages of those gases.

Table 1. Composition of biogas (Aebiom, 2010)

Gas	%
Methane	50-75
Carbon Dioxide	25-45
Water Vapour	1-2
Carbon Monoxide	0-0.3
Nitrogen	1-5
Hydrogen	0-3
Hydrogen Sulphide	0.1-0.5
Oxygen	Trace

The production of biogas is economically and environmentally beneficial as it captures and recovers the methane and carbon dioxide. It is beneficial to remove methane and carbon dioxide as they both considered greenhouse gases which may have a negative impact on the environment. The produced biogas can be used for; heat and/or power generation, vehicle fuel and for national gird injection when upgraded (Figure 1.).

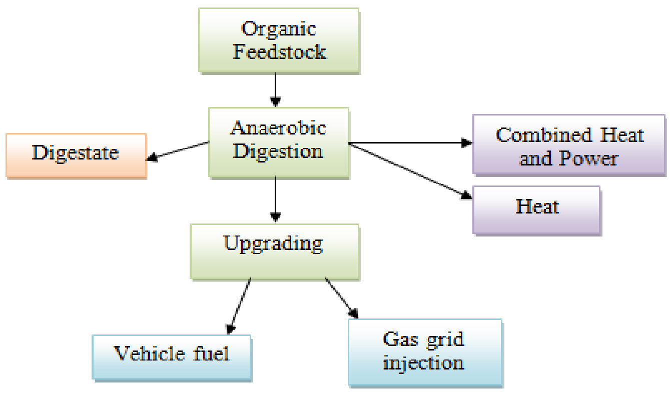

Figure 1. Biogas - an introduction (adapted from Aebiom, 2010)

There is an increasing demand for upgraded biogas, fuelled by an ever growing concern for the environment, climate change and air qualities especially in the urban environment. The European Union is predicted to be responsible for 21 % of the greenhouse gas emissions globally (European Commission 2006, Rasi, 2009).

Bio-methane production can be used to provide a fuel and heat source to promote regional development, as it is more ecofriendly than the extraction on fossil fuels to the environment. Bio-methane production can be used alongside existing transport infrastructures (trains, boat and vehicles). After upgrading it can be injected into existing gas grid locations, vehicle fuels or a high energy fuel. Another important consideration for implementing the use of bio-methane production is that the feedstock or combinations of feedstock and their availability all year around (Persson, 2003).

Combined heat and power plants which use alternative fuels to fossil fuels have been in place for some time, injection of bio-methane into the gas grid is however, rising in public and industrial interests (Urban, 2009).

With regards to carbon dioxide capture from biogas there are now several methods available on the European market. The water scrubber and pressure swing adsorption being the most common in Europe currently where both techniques are technically advanced (Urban, 2009). Cleaning and upgrading technologies that are selected for plants are dependent upon several factors, one of them being the gas quality required (Urban, 2009). Concerning methane losses and gas quality (purity), methane losses can be adapted as required, which leads to higher quality gas and lower methane losses but does increase the profitability of the plant significantly (Urban, 2009).

Where scale is concerned Urban (2009) found that the economics for smaller plants had much higher specific costs that the larger biogas upgrading plants. The economies of scale therefore, show that the larger plants are favoured for producing higher quality gas, lower methane loses, higher plant efficiency and higher profitability (Urban, 2009).

The main objectives of the thesis were to evaluate how the economics of biogas upgrading are influenced by the unit capacity of the biogas upgrading plants. The first objective is to compare the economics of small, medium and large scale biogas upgrading plants in

Europe. The second objective is to evaluate the technical feasibility of small-scale biogas upgrading in Europe

2 BACKGROUND

2.1 Biogas process

In the biogas process, complex proteins, carbohydrates and lipids are broken down under anaerobic conditions by micro-organisms to produce finally methane and carbon dioxide (Ward et al., 2008).

There are four main stages in the biogas process: hydrolysis, acetogenesis, acidogenesis and methanogenesis. Figure 2, is a brief overview of the anaerobic digestion (AD) process, stage by stage. It includes the points where the different biogas components are produced.

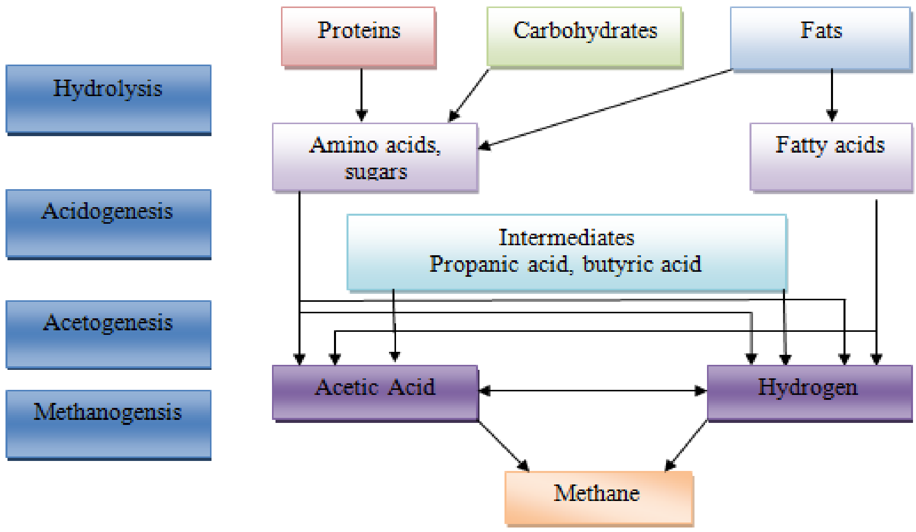

Figure 2. The key process stages of anaerobic digestion (adapted from WtERT, 2009)

There are two temperature ranges which are used on an industrial scale which are mesophilic (30-40 ^{o}C) and thermophilic (45-60 ^{o}C). The other factor that must be monitored closely is pH (Ward et al., 2008).

There are two types of substrate feeding mechanisms which are batch or continuous (Williams, 2008). The moisture level must also be considered for the feedstock it can be wet or dry (Williams, 2008).

2.2 Types of biogas

The composition of the biogas is dependent on the feedstock used Table 2, shows the feedstock options for biogas production. Depending upon the main feedstock used, there are three main types of gases that are produced: sewage gas, landfill gas and AD biogas produced during mono or co-digestion manure, energy crops, industrial wastes etc. in farm-scale or centralized biogas plants (Petersson & Wellinger, 2009).

Table 2. Feedstocks for biogas and their origin (Savola, 2006)

Waste streams	Agriculture
Landfill	Energy Crops
Municipal solid waste	Manure
Sewage sludge	Grass/horticultural
Industrial waste	Other by products
Food waste Other by-products	

Table 3 presents a comparison of the different types of gases commonly used. The table includes two different natural gases, landfill gas and biogas from AD. This table allows a detailed comparison of the parameters from the different gas types.

Table 3. Comparisons of different types of gas (Persson, 2003).

Parameter	Unit	Landfill gas	Biogas from AD	North Sea Natural Gas	Dutch Natural Gas
Lower Heating Value	MJ/Nm^3	16	23	40	31.6
	kWh/Nm^3	4.4	6.5	11	8.8
	MJ/kg	12.3	20.2	47	38
Density	kg/Nm^3	1.3	1.2	0.84	0.8
Higher Wobble Index	MJ/Nm^3	18	27	55	43.7
Methane number		>130	>135	70	N.A.
Methane	vol-%	45	63	87	81
Methane variation	vol-%	35-65	53-70	N.A.	N.A.
Higher hydrocarbons	vol-%	0	0	12	3.5
Hydrogen	vol-%	0-3	0	0	N.A.
Carbon oxide	vol-%	0	0	0	0
Carbon dioxide	vol-%	40	47	1.2	1

Carbon dioxide variation	vol-%	15-50	30-47	N.A.	N.A.
Nitrogen	vol-%	15	0.2	0.3	14
Oxygen	vol-%	1	0	0	0
Hydrogen sulphide	ppmv	<100	<1000	1.5	N.A.
Ammonia	ppmv	5	<100	0	N.A.
Total chlorine (Cl-)	mg/ Nm^3	20-200	0-5	0	N.A.

N.A. Not Available

Landfill gas normally has low methane content (47-55%) compared to sewage gas or gas from AD plants (Persson, 2003). Landfill gas is contaminated by many things such as air as it takes landfills over 25 years to become anaerobic. Rasi (2009) found landfills had a methane quality between 47-62%. Landfill gas and sometimes sewage gas can contain siloxanes, whereas all types of biogas contain hydrogen sulphide, carbon dioxide and water vapour.

The biogas yield and methane content depends upon the feedstock and its composition. Table 4 presents the composition for biogas substrates and the final methane yield and content. This table is based on theoretical assumptions but in practice the yields are much lower than the figures given in the table reference.

Table 4. Biogas yield and methane content (Petersson & Wellinger, 2009).

	Biogas Yield (m^3/t VS)	Methane Content by Volume %
Fat	1000-1250	70-75
Protein	600-700	68-73
Carbohydrate	700-800	50-55

3 CLEANING AND UPGRADING OF BIOGAS

3.1 Uses of upgraded biogas

The raw biogas can be combusted in a boiler though it does have a lower calorific value. The upgraded biogas can be used for injection to the national gas grid, vehicle fuel, material for the chemical industry and a high energy fuel for the heat and electricity generating industry. The upgraded biogas can be utilized in many ways but local use is still the most common option and the most economically viable (Ryckebosch et al., 2011).

3.2 Cleaning technologies

Biogas cleaning is the process where any impurities are removed such as sulphides and ammonia. Biogas upgrading on the other hand is the process which removes carbon dioxide and the end product is bio-methane. The bio-methane which has been upgraded is suitable for injection into the national gas grid or vehicle fuel. Biogas needs cleaning for two main reasons; the first is to improve the calorific value of the product gas and the second is to reduce the chance of damaging downstream equipment which is due to the formation of harmful compounds (Ryckebosch et al., 2011).

Water vapour

Biogas contains water vapour. The removal of water vapour is essential as it combines with the other contaminants such as hydrogen sulphide or halogenated compounds to produce corrosive acids. The main reason it is important to remove water is to prevent damage to pipes and engines when injecting into the gas grid (Person, 2003). The water vapour can be removed in a number of ways, for example adsorption with silica gel, glycerol, refrigeration, sensible piping, activated carbon or molecular sieves (Petersson & Wellinger, 2009).

Hydrogen sulphide

The mostly commonly found sulphide gas is hydrogen sulphide which is mainly a component of landfill gases. There are four main ways that hydrogen sulphide is removed; precipitation, adsorption with activated carbon, chemical absorption and biological treatment. An example of chemical absorption would be the insertion of sponges to the pipeline, which cause a chemical reaction (Cheng, 2010).

Hydrogen sulphide can also be removed using certain oxides. SulfaTreat® is a brand which makes granules based on these combinations which can be found naturally (Alterner Programme, 2001).

Hydrogen sulphide can be reduced by injecting air (Alterner Programme, 2001), activated carbon (Petersson & Wellinger, 2009), adding chemical filers or bio-scrubbers (Cheng, 2010) into the biogas mixture during the cleaning process.

If the upgraded gas is intended for vehicle fuel then oxygen cannot be present in large amounts, then it is most common to use potassium iodide as the activated carbon and catalyst (Petersson & Wellinger, 2009).

Biological treatment

Biological treatment is a process where biological filters are used that contains micro-organisms (chemo-autotrophic), which require oxygen (Zhao, et al, 2010). Mesophilic conditions give a complete reaction and the thermophilic reaction gives a rapid methnogenesis reaction (Ryckebosch et al., 2011). It can remove both carbon dioxide and hydrogen sulphide (Ryckebosch et al., 2011).

The removal of particulates

Particulates can be separated by a variety of mechanical filters which can be made from many different materials such as paper or fabric. There can be traces of oil and other hydrocarbons which are also removed using these filters. This kind of cleaning can be done before upgrading or before injection into the natural gas grid or transport fuel storage (Persson, 2003).

The removal of ammonia

Ammonia is formed when proteins are broken down during AD, depending on the amounts of feedstock and the amount of protein present the levels of ammonia are normally quite low. Ammonia can be removed when water is removed when separating the condensed water but it can also be removed when removing the carbon dioxide using water scrubbing (Kim 2002, Persson, 2003).

The removal of halogenated hydrocarbons

Are most commonly found in landfill gas but can rarely be found in sewage gas and organic waste gas. They are very corrosive when they combine with water. Polychlorinated dibenzo-para-dioxins (PCDD) and polychlorinated dibenzo-furans (PCDF) are persistent organic pollutants which are normally an unwanted by-product of combustion of biomass but can be found in sewage gas also. Persistant organic pollutants form a risk to human health and also to the environment (Petersson & Wellinger, 2009, Black et al., 2011).

Halogenated hydrocarbons are most commonly removed using absorption technologies with activated carbon. Activated carbon can be regenerated but not indefinitely (Persson, 2003).

The removal of oxygen

Oxygen can be removed whilst removing other contaminants. For example, oxygen can be removed using membrane separation technologies with carbon dioxide.

The removal of siloxanes

Siloxanes are only found in gases which originate from landfill or sewage feedstock. Siloxanes can be removed using active carbon adsorption, activated aluminum or silica gel (Petersson & Wellinger, 2009).

3.3 Upgrading technologies

Biogas upgrading is an important process to meet the requirements of gas quality for grid injection, to improve the calorific value of the gas, make sure the gas is standardized in its components, reduce negative effects on the environment and reduce the gas volume by compression. Figure 3, gives the main processes normally used for biogas upgrading technologies.

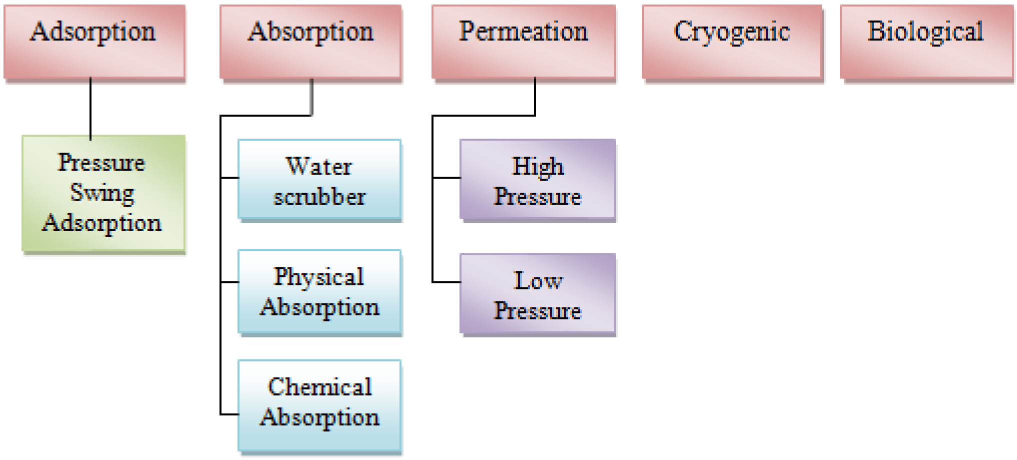

Figure 3. Upgrading technologies options (adapted from ISET, 2008)

The five main upgrading technologies are; PSA, absorption with water (water scrubbing), absorption with chemicals, membrane separation and cryogenic separation.

3.3.1 Pressure Swing Adsorption (PSA)

PSA is a technology where gases are separated under pressure which is dependent on their ability to penetrate the material and remove the unwanted contaminant/s. PSA technology is very flexible and can absorb a broad range of contaminants in gases or liquids (Grande & Rodrigues, 2007, Ryckebosch et al., 2011)

Zeolites (highly porous) are the most common commercial adsorbent which act as molecular sieves (Persson, 2003, Alonso—Vicario et al., 2010). The absorbed gases is then desorbed from the zeolites but decreasing the pressure, allowing regeneration (Persson, 2003, Alonso—Vicario et al., 2010). However activated carbon (Grande & Rodrigues, 2007), natural zeolites (Ackley, 2003, Ryckebosch et al., 2011) silca gels and activated aluinas (Ryckebosch et al., 2011).

The purified gas has a purity of around 97% methane (Ryckebosch et al., 2011). PSA can also be used to upgrade landfill biogas (Cavenati, 2005, Rasi, 2009). De Hullu et al. (2008) estimated the cost of PSA method to be 0.40 €/Nm^3 biogas. This process does require hydrogen sulphide removal prior to this stage.

Figure 4, shows PSA process and its ability to retain some gases under varying pressures and remove others (Gladstoner, 2007, Ryckebosch et al., 2011).

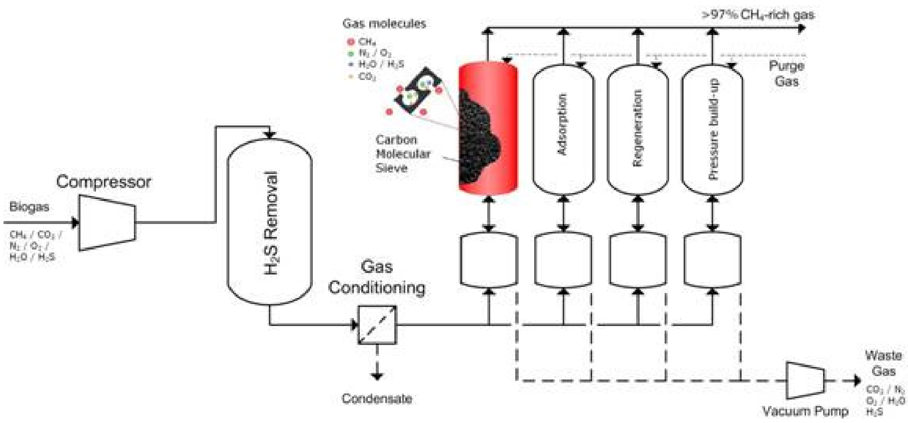

Figure 4. Pressure Swing Adsorption process (ISET, 2008)

3.3.2 Absorption with water (water scrubbing)

Absorption with water involves using pressurised water and changes in temperature which removes carbon dioxide, hydrogen sulphide and ammonium (Persson, 2003). Water and particulates should be removed before this stage (Alterner Programme, 2001). It can be single passed or recirculated (Rasi, 2009, Ryckebosch et al., 2011).

The biogas is pumped into the bottom of the column and the water at the top of the column which gives a co-counter flow to increase the efficiency of the system. The column is packed with material to give a higher surface area for the gas and water to interact, the carbon dioxide gas is then absorbed by the water (Alterner Programme, 2001, Ryckebosch et al., 2011). The water cannot be recycled (Ryckebosch et al., 2011). Figure 5, shows carbon dioxide removal with water scrubbing on a non-regenerative process.

According to de Hullu et al. (2008) the cost of the water scrubbing method is 0.13 €/Nm^3 biogas.

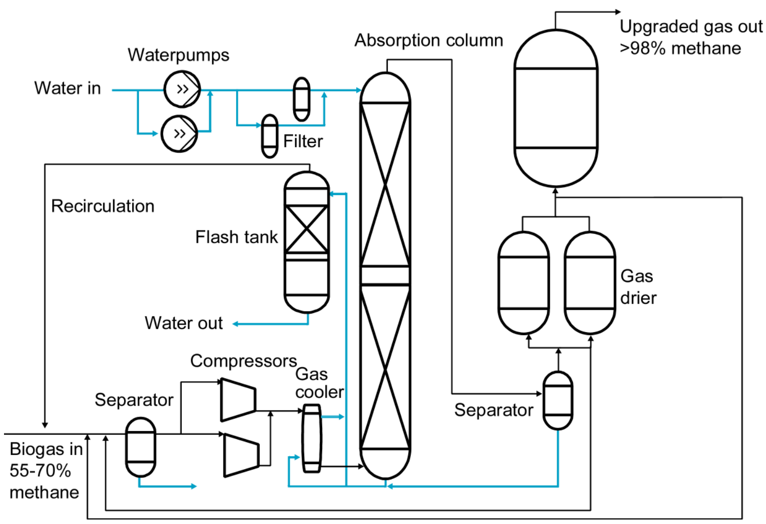

Figure 5. Carbon dioxide removal with water wash, not regenerated (Ryckebosch et al., 2011).

3.3.3 Absorption with chemicals (Chemical Scrubbing)

The pressure and the temperature are altered to remove the unwanted gases which are then absorbed into the absorption chemical (Cheng, 2010). The absorber has a high cost therefore; it is always recycled. The process is continuous with chemical absorption and the absorber is regenerated using a reverse chemical reaction where the carbon dioxide is released (Alterner Programme, 2001, Ryckebosch et al., 2011).

De Hullu et al. (2008) evaluated the price of the upgraded biogas using this technique to be 0.17 €/Nm^3.

3.3.4 Physical absorption with organic solvents

There is a gas removal solvent which can remove acid gases such as hydrogen sulphide and carbon dioxide, its trademarked name is Selexol®. Selexol® is dissolved into water and removes both hydrogen sulphide and carbon dioxide at the same time. There are also many other solvents available for use with this process.

Selexol® can dissolve many times more carbon dioxide than water, this allows for smaller facilities to be built decreasing economic costs. The negative side of Selexol® being so absorbent is it is difficult to regenerate (Persson, 2003, Ryckebosch et al., 2011).

Selexol® is fed from the top of the column to achieve a gas-liquid counter flow. The column is equipped with a suitable packing material to give a large surface. The waste gas leaves the top of the column and the flash tank is depressurized, air is then pumped into the bottom to remove any remaining carbon dioxide (Alterner Programme, 2001).

Figure 6, is the biogas upgrading process using both SulfaTreat® and Selexol®.

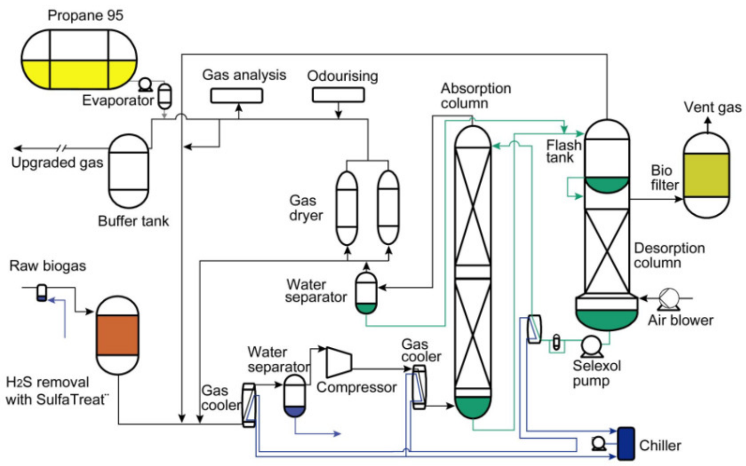

Figure 6. Upgrading with SulfaTreat® and Selexol® (Persson, 2009).

3.3.5 Membrane separation

Membrane separation can occur under both wet and dry conditions depending on what substances are being removed. The diffusion rate is dependent on partial pressure, membrane thickness and the chemical solubility of the substance (Ryckebosch et al., 2011). There is low and high pressure separation, gas-gas and gas-liquid separation (Ryckebosch et al., 2011)

Permeability is an important factor where carbon dioxide and hydrogen sulphide can then pass through the membrane (fibre wall), while methane is retained. The upgrading process remains at high pressure, so no further compression is needed before addition to the gas grid (Alterner Programme, 2001, Ryckebosch et al., 2011). The main principle of membrane separation constitutes a conflict between high methane purity in the upgraded gas and high methane yield around 92% (Ryckebosch et al., 2011).

De Hullu et al. (2008) predicted the cost of this technology to be 0.12 €/Nm^3.

3.3.6 Cryogenics

The raw biogas is compressed in multiple stages with intercooling which allow the gas to be further compressed each time. The compressed gas is dried to avoid freezing in the following cooling process. The gas is cooled to approximately -55 °C by heat exchangers.

The pressure is then altered and the temperature is decreased to -110 °C. The gas phase, which consists of more than 97% methane, is heated before it leaves the plant (Alterner Programme, 2001, Ryckebosch et al., 2011). Hydrogen sulphide should also be removed prior to this process (Persson, 2003). De Hullu et al. (2008) states this process is 0.44 €/Nm^3.

Figure 7, shows the cryogenic separation process for the removal of carbon dioxide.

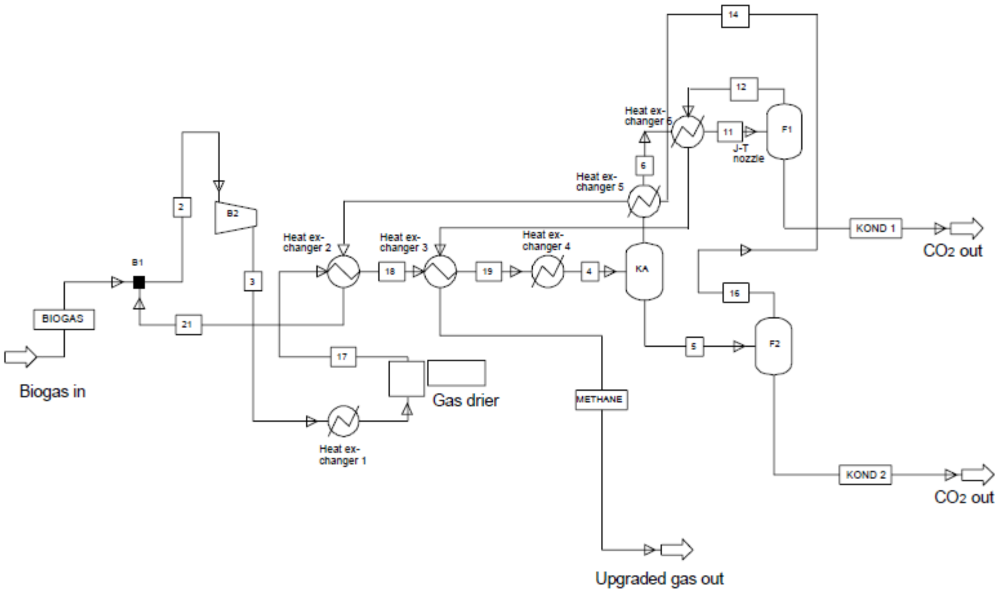

Figure 7. Cryogenic separation process for the removal of carbon dioxide (Alterner Programme, 2001).

3.4 Economic considerations

Economics is the main driving factor in industry and it is critical for a company's survival that it makes a profit. It includes information on investment costs, annual costs (operating, personnel, maintenance) and specific costs of the bio-methane at different stages, all of these things were assessed at different scales.

3.5 Scale of upgrading

The cost of biogas upgrading is influenced by scale, there are other factors which have an impact on economics such as the specific type of biogas upgrading technology which is selected but the most important factor for economic consideration is the scale of the biogas upgrading plant (Petersson & Wellinger, 2009). There are currently plants available with capacities lower than 250 Nm^3/h and with capacities higher than 2,000 Nm^3/h (Petersson & Wellinger, 2009).

With regards to the scale of upgrading for large scale plants, the main conclusions of upgrading costs are that they are dependent upon the plant size. (Jönsson, 2004). For small scale plants (<100 Nm^3 $hour^{-1}$) the upgrading costs are around 0.03-0.04 € kWh^{-1} and large plants between 200-300 Nm^3 $hour^{-1}$upgrading costs are 0.01-0.16 € kWh^{-1} (Rehnlund & Rahm, 2007).

According to Persson (2003) total costs are for 200-300 Nm^3 / h biogas upgrading plants about 1-1.5 cents / kWh bio-methane, whereas according to Urban et al (2009) for a 250 Nm ^{3} / h biogas upgrading plants the total costs stand at about 2.23 € / kWh bio-methane (Urban 2009, Ahonen, 2010).

3.5.1. Economics of upgrading

Persson (2003) was used as a base for information on technology and economics, it was then compared to Urban (2009) to see if there was any variation in the economics for the investment costs, upgrading or cleaning technologies.

De Hullu et al. (2008) does not mention scale but chemical absorption investment costs for carbon dioxide and hydrogen sulphide removal are 869,000 €, PSA the cost is around 680,000, cryogenics is the most expensive option and for membrane separation the cost is 233,000 €.

According to Urban (2009) the investment costs for a biogas upgrading plant treating 500 Nm^3 biogas / h are on the average one million euros, while for a plant treating 2,000 Nm^3 biogas / h the investment costs are close to three million euros. Investment costs (€/Nm^3 biogas) decrease as size of the plant increases; for a plant treating 2,000 Nm^3 biogas / h the costs are 1,500 €/Nm^3 and for a plant treating 500 Nm^3 biogas / h the costs are on average 2,300 €/Nm^3. The biggest differences in investment costs seem to reside between equipment manufacturers, and not so much between upgrading methods. Investment costs are on the same level with the data collected by (Persson 2003, Ahonen, 2010).

De Hullu et al. (2008) predicts service/maintenance costs of around 50,000 € annually including one annual internal and external inspection of the plant. Urban (2009) estimates that the maintenance costs are around 2 % of the predicted capital costs. The water costs is assumed by Urban (2009) to be around 2 €/m^3.

De Hullu et al. (2008) predicts the operational costs for chemical absorption for carbon dioxide and hydrogen sulphide removal 179,500 € annually. High pressure water scrubbing costs from de Hullu (2008) were 110,000 €. According to de Hullu et al. (2008) PSA operational cost is 187,250 €. Cryogenics operational cost is 397,500 € and membrane separation is 81,700 €.

Urban (2009) stated that the substrate cost had a large influence on the cost of biogas production and when the substrate prices are over 35 €/tonne it can result in plants having a low income or even a negative income. Urban (2009) adds that it is beneficial to the plants if they can agree with substrates suppliers a long term price for the product

Development in biogas upgrading methods can lead to the cost evaluations to expire quite rapidly. Persson (2003) reported that the investment costs for Swedish biogas plants treating about 250 Nm^3 biogas/ h are similar to the costs collected from equipment manufacturers by Urban (2009). Total costs for biogas upgrading, however, are significantly different.

In the cost data given by cleaning equipment manufacturers the methane concentration of the biogas is set to 53% (Urban et al 2009). Methane concentration of the cleaned gas is 97% according to the manufacturers (Ahonen, 2010).

The operating costs for biogas upgrading plants increases as the size of the facilities also increase. Operating costs for a plants around 500 Nm^3 biogas / h are on average 220, 000 €/y. As the investment costs, also the operating costs per $Nm^3$of biogas will be lower in larger upgrading units. Operating costs for a plant treating 500 Nm^3 biogas / h are 440€/Nm^3 while for a plant treating 2,000 Nm^3 biogas / h the cost are about 340€/Nm^3 (Urban et al 2009, Ahonen, 2010).

With regards to Urban (2009) all the capital and operating costs of the individual systems and procedures between 2007 and 2008 are the respective numbers given by companies. Although in some cases they were very close to the market prices, all the subsequent cost figures can be understood only as reference prices. In particular, the model cannot account for all cases (Urban, 2009).

4 METHODOLOGY

The main objectives of this thesis were to evaluate the effect of scale on the techno-economics of biogas plants in Europe. The first objective is to compare the economics of small, medium and large scale biogas upgrading plants in Europe. The second is to evaluate the technical feasibility of small scale biogas upgrading in Europe. This study used a self-designed questionnaire which was sent to biogas plant owners/operators. The questionnaire aims to collect primary data for the technical issues, process conditions, biogas production, the upgrading system, energy use and economics in relation to scale.

The questionnaire focuses on issues such as the scale of the biogas plant, feedstock and process conditions such as organic loading rate, operating temperature and biomass feed rate. Biogas production conditions such as the amount of biogas produced a day, the methane content, the end use of the upgraded gas and the water consumption of the plant. Furthermore, the type of upgrading technology, the capacity of the technology, methane losses, how the upgraded biogas is transported, methane yield and the content of the upgraded biogas were assessed. The use of energy is also assessed inquiring how much energy was consumed. The final section of the questionnaire covered economic issues such as what the capital costs were for investment, final cost of upgraded biogas, operational costs and process costs.

As an addition, if the questionnaires do not get the number of responses required then an in-depth literature review will be carried out using Urban (2009) report as the main report for the economics of biogas and the effect the scale has on that cost. Fifty questionnaires were sent out but there were only two responses.

De Hullu et al. (2008) explored different biogas upgrading techniques but didn’t mention scale. There was no methodology in this thesis. Some of the costs were footnoted to have been taken from other sources, some of which are companies which supply biogas upgrading technologies. It is also unknown if the results were subjected to any kind of statistical analysis as it is not mentioned in the report. This report was used to give an idea about the costs of the five biogas upgrading technologies as there is a difference in costs for the technologies which affects the costs at any scale. The thesis did not require any evaluation into upgrading technologies that were not related to scale and the scale at which those costs evaluated at in de Hullu et al. (2008) were not mentioned either, this is important with regards to the economy of scale. It was not therefore, possible to compare scales using de Hullu et al. (2008).

Urban (2009) was a very useful report as it did relate scale to the costs of certain biogas upgrading technologies. The results were probably collected by questionnaire to the biogas upgrading technology companies. There was a difference in the scales used, the scales in this thesis were much smaller that the scales used in Urban's report. The effect of scale should be the same though, the bigger the plant, the more efficient the process, higher yields but a higher startup cost. This report formed the backbone of the results for this thesis as they provided economic information that was compared by the scale of the plant size, this allowed an easy comparison.

The scale used in this thesis was small scale <100 m^3/hour, medium scale 100-250 m^3/hour and large scale 500 m^3/hour. The main source for economics comparisons were taken from Urban (2009) which provides costs in relation to scale for upgrading technologies, cleaning technologies and the investment costs from some manufacturers. Urban (2009) uses three main different types of scales dependent on subject being assessed but all very between 100 Nm^3/hour, 250 Nm^3/hour and 500 Nm^3/hour, however a few tables explore options which are 1,000 Nm^3/hour and 2, 000 Nm^3/hour. Urban (2009) states that the economies of scale favour larger biogas plants, the desired scale should be between 500 and 1,400 Nm^3/hour of raw biogas.

Persson (2003) although this report is older than normally used it was a very useful source of detailed information on biogas upgrading technologies in Sweden. The information was gathered by collecting data for the Swedish Gas Center. Persson's report data was obtained by questionnaires, surveys, interviews and site visits. The information was gathered from site/plant owners and from a literature review. This report was used to gain a deeper insight into the technology and some other economic considerations. There was no information in regards to scales which could have been used in this thesis. There was no mention whether statistical testing was used to compare the results. The economics in Persson's report were compared to other reports such as De Hullu et al. (2008) and Urban (2009) to check if the economics were still valid, some were ok and some others were outdated.

Alterner Progamme (2001) this report is the oldest document used and is too old to use any technical information even if it were available but the information about the technologies was explained in depth and still relevant. It also gave basic information on most European countries as a baseline to start researching which countries were best for biogas upgrading and utilisation. This report did not state how the information was gathered or whether any results had been tested statistically. The results were not comparable if they contained economics as the report is too old.

Ahonen (2010) is a master's thesis which explores the use of biofuel use and there cleaning costs in central Finland. The methods were a literature review. This report was useful to compare the results for Urban (2009). This report was used to check for further information and to confirm the self-translation from Urban (2009).

Rasi (2009) is a Ph.D. dissertation which explores biogas composition and upgrading. This dissertation provided an in depth guide into small scale biogas upgrading and landfill biogas upgrading. The information used in this thesis was obtained by literature reviews and experiments. The experiment allowed a more in depth use for landfill gas figures.

Ryckebosch et al. (2011) evaluates biogas upgrading provided some detailed information on the biogas upgrading technologies. This was peer reviewed so is an important source of information. The results were collected by literature review. The data was used in the thesis to strengthen the significance of the information used from the older reports.

5 RESULTS

5.1 Biogas upgrading technologies status

Biogas upgrading has been used in Europe for around 20 years. The current EU situation according to Kaparaju (2011) there were 137 biogas upgrading units in Europe. It also shows the type of upgrading technology chosen by industries.

Figure 8, shows the types of technologies used by the 137 plants. From these 137 plants during 2011, the total raw gas capacity used for biogas upgrading in Europe was 115,155 Nm^3 hour $^{-1}$. The most common technologies are PSA, water scrubbing and chemical scrubbing (Kaparaju, 2011).

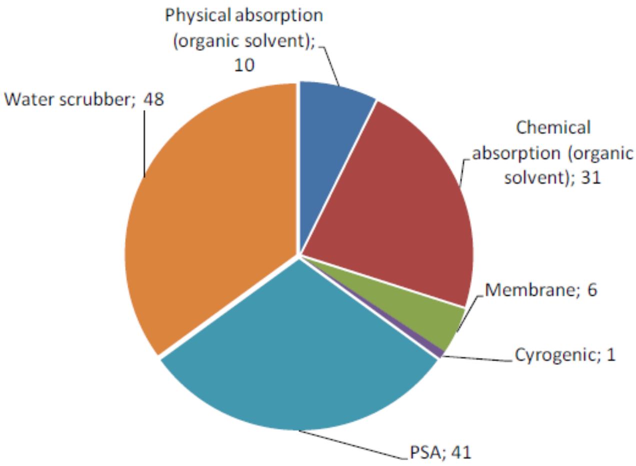

Figure 8. Amount of biogas upgrading plants in Europe (Kaparaju, 2011).

Figure 9 shows that during 2011, the total capacity of water scrubbing was 46,440 Nm^3 $hour^{-1}$, chemical scrubbing was the next popular technology 32,170 Nm^3 $hour^{-1}$ and then PSA at 20,230 Nm^3 $hour^{-1}$ (Kaparaju, 2011).

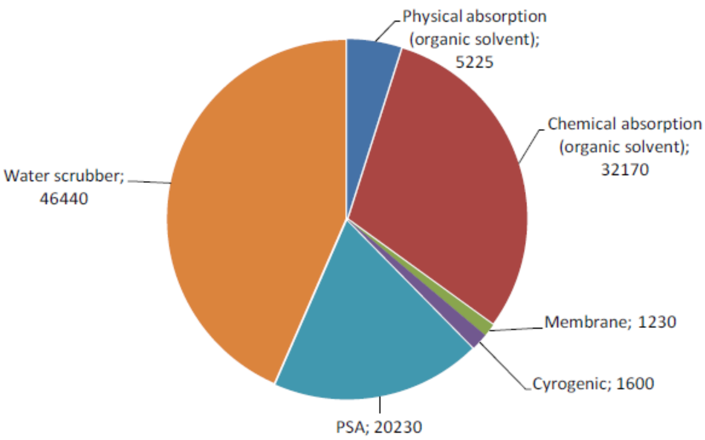

Figure 9. The types biogas upgrading technologies used in Europe (Kaparaju, 2011).

The current situation in Europe is shown in Table 5 which gives a small example of biogas upgrading plants in Europe taken from IEA Bioenergy including Country, location, feedstock, utilization, technology, raw gas capacity and the length of the time the facility has been operational (Petersson & Wellinger, 2009). The scale used in this thesis was small scale <100 m^3/hour, medium scale 100-250 m^3/hour and large scale 500 m^3/hour. The table below shows a small extract from Petersson and Wellinger (2009) there is more small scale biogas upgrading plants currently in Europe. The table gives the country, location, feedstock, upgrading technology type, the utilisation of the upgraded biogas, capacity of the plant and the year the plant became operational. Petersson and Wellinger (2009) full table shows that the countries that have the most places are Sweden, Germany, the Netherlands and Austria.

Table 5. Biogas upgrading plants operating equipment from the manufacturers (Petersson & Wellinger, 2009)

Country	Location	Substrate	Utilisation	Technology	Capacity Nm^3/h raw biogas	In Operation Since
Austria	Pucking	Manure	Gas grid	PSA	10	2005
Austria	Leoben	Sewage sludge, bio-waste	Gas grid	Chemical scrubber	140	2009
Germany	Aiterhofen	Energy Crops	Gas grid	PSA	2,000	2009
Germany	Zörbig	Bio-waste	Gas grid	Chemical scrubber	10,000	2010
Germany	Güstrow	Energy crops	Gas grid	Water scrubber	10,000	2009
Germany	Schwandorf II	Energy crops	Gas grid	PSA	2,000	2008
Spain	Vacarisses (Barcelona)	Landfill gas	Vehicle fuel	Chemical scrubber	100	2005
Sweden	Göteborg	Sewage sludge, bio-waste	Gas grid	Chemical scrubber	1,600	2007
Sweden	Kristianstad	Bio-waste, manure, sewage sludge	Vehicle fuel	Water scrubber	600	2006
Sweden	Jönköping	Sewage sludge, bio-waste	Vehicle fuel	Water scrubber	300	2000

5.2 Economical evaluation of scale for biogas upgrading

Table 6 shows the economic information received from the questionnaires. The scale used in this thesis was small scale <100 Nm^3/hour, medium scale 100-250 Nm^3/hour and large scale 500 Nm^3/hour. Most economic information was not available for Kristianstad so no comparison can be made.

Table 6. Economical evaluation from the raw data

Property	Kalmari's Farm	Kristianstad
Cost of upgrading equipment	€ 250,000	€ 1,921,100 (17 MSEK)
Cost of installation and odour control	€ 30,000	N.A
Cost of feed compressor	€ 20,000	N.A
Maintenance costs	500 €/month	N.A
Energy costs	600 € /month	N.A

N.A Not Available

Figure 10 shows the upgraded biogas price per Nm^3 biogas/hour for small scale biogas plants 0-100 Nm^3 biogas/hour. Lems and Dirkse (2010) concluded that 20 to 25 Nm^3/h of upgraded gas must be produced to obtain a production price of approximately 0.20- 0. 30 € per Nm^3. This figure evaluates the upgraded biogas price in relation to scale, this allows for plants to judge if biogas upgrading is economically viable.

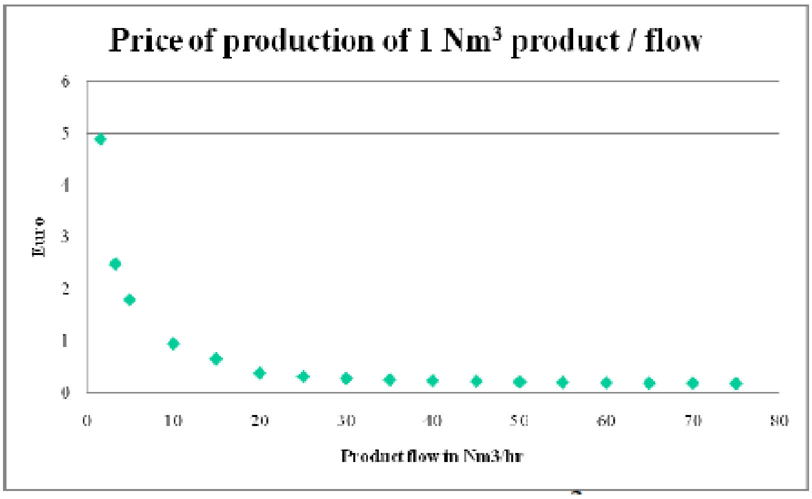

Figure 10. Biogas price per Nm^3 biogas/hour for small scale (Lems & Dirkse, 2010)

Table 7 gives an economics estimate for the main biogas upgrading technologies for medium scale biogas upgrading technologies 250 Nm^3 biogas/hour. For BioSling® the economic information was not available without request and is priced by quotations. The table gives information on water scrubbing, PSA, chemical scrubbing, membrane separation and cryogenics in relation to their costs. Cryogenics is the most expensive for investment cost, maintenance costs and for cost per Nm^3/biogas upgraded. Membrane separation was the lowest price for investment cost, maintenance cost and for cost per Nm^3/biogas upgraded. It is worth noting that PSA is the second most expensive for investment and maintenance costs.

Table 7. Biogas upgrading plants operating equipment from the manufacturers (de Hullu et al., 2008)

	Water Scrubbing	PSA	Chemical Scrubbing	Membrane Separation	Cryogenic
Investment Cost (€/year)	€ 265, 000	€ 680, 000	€ 353, 000 - 179, 500	€233, 000 - 749, 000	€ 908, 500
Maintenance Cost (€/year)	€ 100, 000	€187, 250	€134, 000 - 179, 500	€ 81, 750 - 126, 000	€ 397, 500
Cost per Nm^3/biogas upgraded	0.13 €	0.25 €	0.17 - 0.28 €	0.12 - 0.22 €	0.44 €

N.A Not Available

Figure 11 shows scale vs. economics for Swedish biogas upgrading plants where the larger the plant, the more volume of biogas that can be processed and the larger the upgrading capacity has to be.

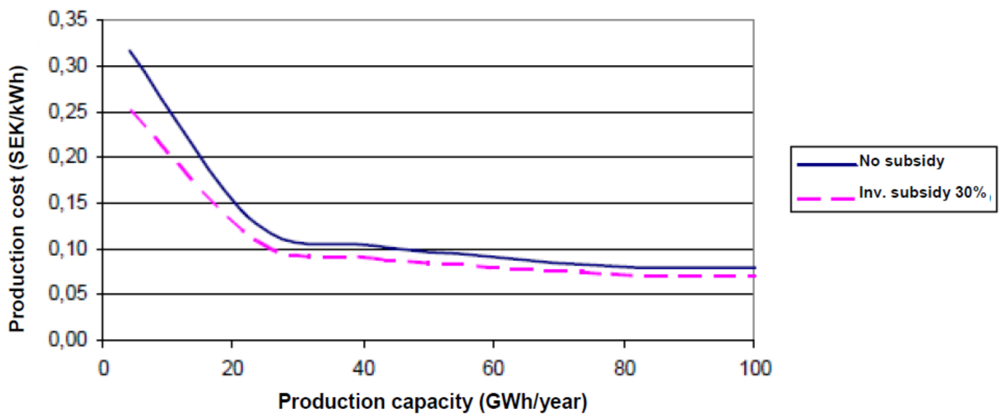

Figure 11. Investment costs for Swedish biogas upgrading plants (Palm, 2010, Grontmij, 2009).

Figure 12 shows another version of scale vs. economics with regards to how the operational and maintenance costs increase with plant size. It shows that with an increase in scale (larger plants) that the cost in operation and maintenance also increases.

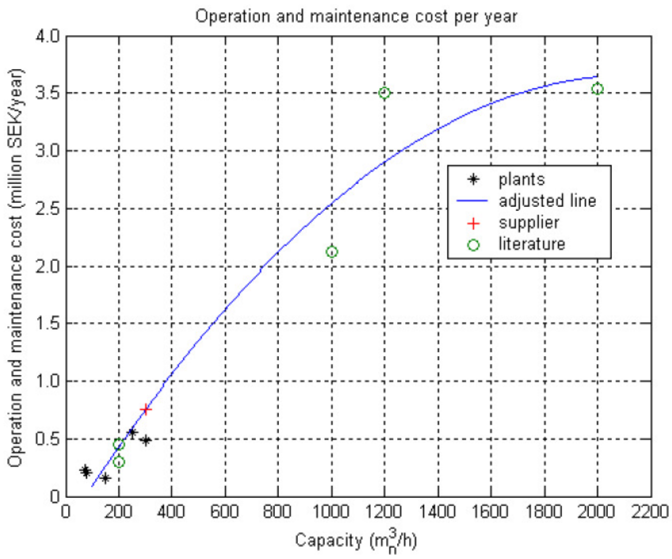

Figure 12. Operational and maintenance costs in literature (Persson, 2003).

Figure 13 plots economy vs. scale for the different technologies and different scales for the upgrading technologies. The graph shows that for all three processes the cost decreases when the capacity of the biogas plant increases.

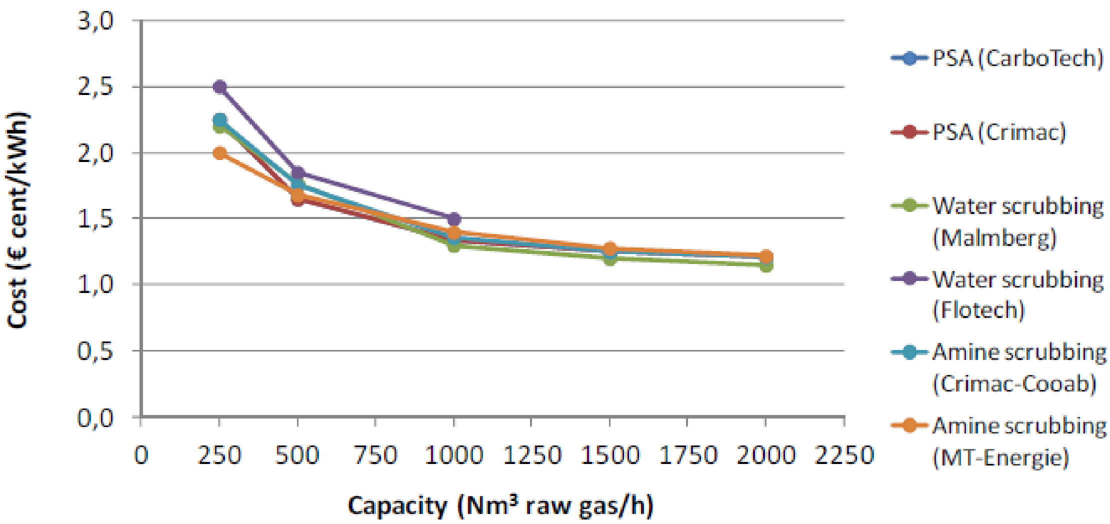

Figure 13, Cost for biogas upgrading for methane (Petersson, 2009).

Figure 14-16 shows graphically the German Fraunhofer Institute has collected investment, operating and total costs for biogas upgrading from five purification equipment manufacturers during 2007-2008. These manufacturers are Carbotech (PSA), Cirmac (PSA, chemical absorption), Malmberg (water absorption), Flotech (water absorption) and MT-Energie (chemical absorption). Flotech has only provided total costs of the biogas upgrading technology. Then it is assumed that the methane content of the raw biogas is 53% and the methane content of the purified gas is 97%. The cost data includes sulphur dioxide removal in those biogas upgrading methods where it is necessary. The expected losses of methane in different upgrading methods are as follows: PSA 3%, water absorption (Malmberg) 1%, water absorption (Flotech) 2%, chemical absorption 0.1% (Urban et al, 2009, Ahonen, 2010).

Figure 14 shows graphically the German Fraunhofer Institute has collected investment, operating and total costs for biogas upgrading from five purification equipment manufacturers during 2007-2008. These manufacturers are Carbotech (PSA), Cirmac (PSA, chemical absorption), Malmberg (water absorption), Flotech (water absorption) and MT-Energie (chemical absorption). PSA (Carobtech) has the largest investment cost, followed by water absorption (Malmberg), PSA (Cirmac), chemical absorption (MT Energie) and lastly chemical absorption (Cirmac) this once more shows differences between the different manufacturers and for different types of upgrading technologies.

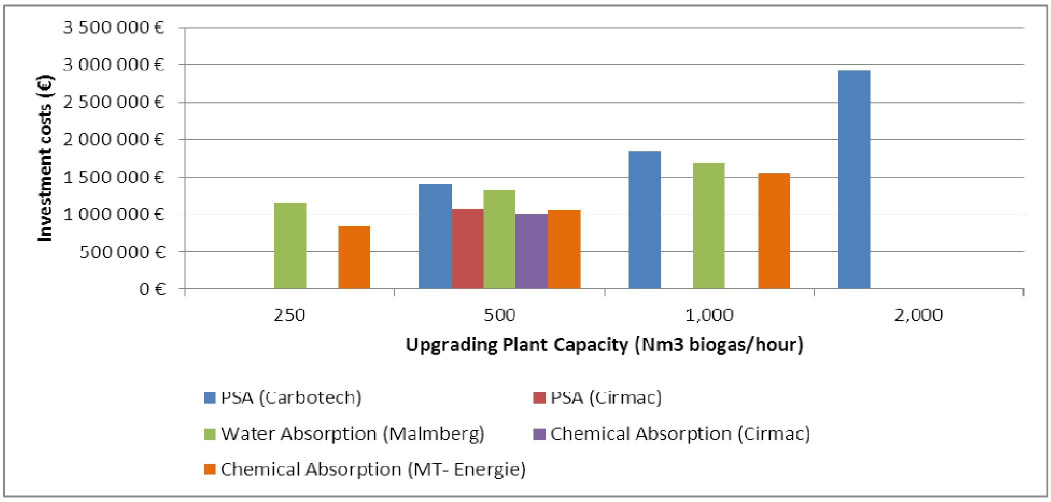

Figure 14. Upgrading equipment indicated by the manufacturers of biogas upgrading plants for investment costs (Urban, 2009)

Figure 15 shows operating costs vs. upgrading technologies, it does not include investment costs. The larger the scale the higher the maintenance costs as there is more equipment to be maintained. This shows that scale is affected by the operating costs as well as variance in manufacturer's prices. For large scale plants over 2,000Nm^3 biogas/hour, PSA (Carbotech) is the most expensive. Small scale (250Nm^3 biogas/hour) there is no big difference between the operating costs for water absorption (Malmberg). Medium scale

(500Nm^3 biogas/hour) chemical absorption (Cirmac) has the highest operating costs, then PSA (Cirmac), chemical absorption (MT Energie), water absoption (Malmberg) has the lowest operational costs.

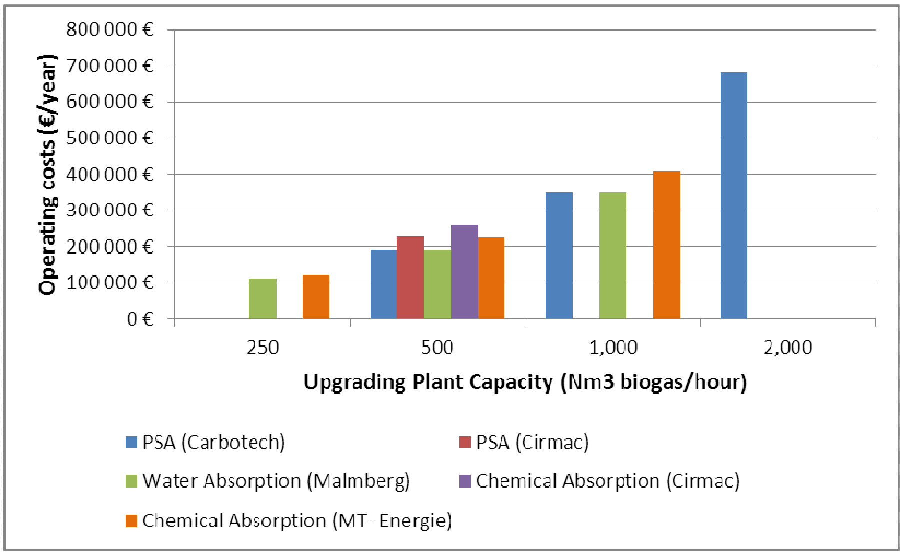

Figure 15. Operating costs for various upgrading technologies and plant capacity (Urban, 2009)

Figure 16 shows graphically the total costs (€/kWh bio-methane) of biogas upgrading plant equipment from the manufacturer. It concludes that the larger the scale the lower the total costs per €/kWh of bio-methane. Once more there are still differences between the manufacturer's prices as well as differences in the upgrading technologies at different scales.

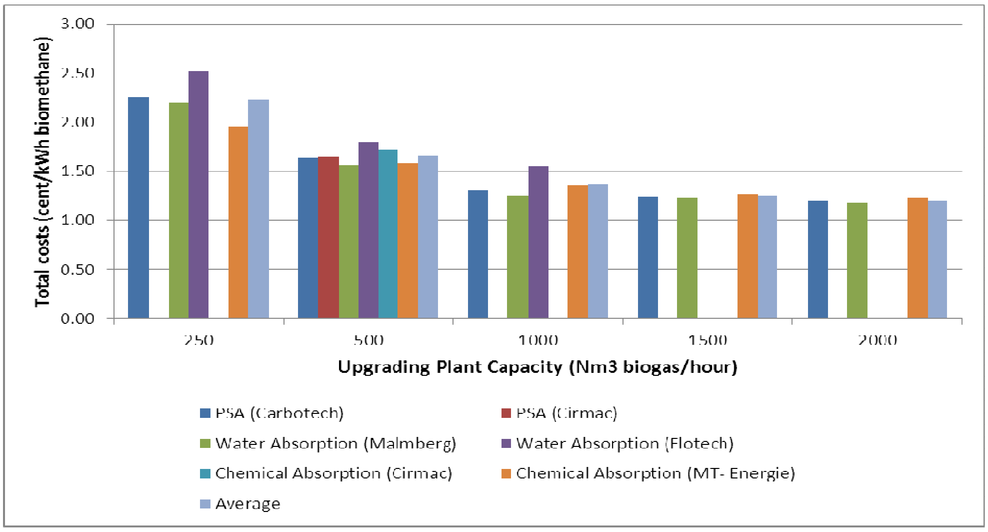

Figure 16. shows graphically the total costs (cent/kWh biomethane) of biogas upgrading plant equipment from the manufacturer (Urban, 2009)

De Hullu et al (2008) evaluates that cryogenics is the most expensive form of upgrading technologies, followed by PSA, chemical scrubbing, water scrubbing and finally the cheapest membrane separation. However, Urban (2009) concludes that there are differences in which technology is cheapest and it relates to the scale of the biogas upgrading plant. For example, according to Urban (2009) for small scale plants (<250 Nm^3/hour) water scrubbing (Flotech) is the most expensive, followed by PSA, water scrubbing (Malmberg) and finally chemical scrubbing. For medium scale (251-500 Nm^3/hour) the most expensive process is water scrubbing (Flotech), chemical scrubbing (Cirmac), PSA, chemical scrubbing (MT Energie) and finally water scrubbing (Malmberg). Large scale over 1,000 Nm^3/hour was evaluated to have water absorption (Flotech), chemical absorption (MT Energie), PSA and water scrubbing (Malmberg). Urban's (2009) evaluation of suppliers concludes that there are noticeable price differences between suppliers of types of biogas upgrading technology, prices are therefore, affected by scale and by the price the manufacturers set for the technologies.

According to the data collected by the Fraunhofer Institute, the total costs of biogas cleaning (kWh per bio-methane) will decrease when the treatment plant capacity increases. The total cost for a biogas plant treating 250 Nm^3 biogas / h are on average 2.23 €/kWh bio-methane, whereas for a plant treating 2,000 Nm^3 biogas / h the costs are approximately 1.20 €/kWh bio-methane. These estimates are based on a 15-year payback time for the investment with an interest rate of 6 % (Urban, 2009, Ahonen 2010). This is an important consideration to include into investment costs.

In Table 8 biogas production costs are shown. The data was calculated by UMSICHT using the completed biogas plants as average prices for installations in the medium price range with a high degree of automation and they refer to an example of the "manure-biogas plant" (manure fermentation, 90 % manure and 10% corn silage) also for an exemplary "energy crops biogas plant" (fermentation of renewable raw materials, 90% corn silage and 10% manure, cover the fresh weight). All the calculations have an assumed substrate price of 35 €/t fresh weight (corn silage). The cost figures below are a good management with appropriately trained personnel. The information may therefore differ materially from practical values (Urban, 2009). The figures from the table show that investment costs, decommissioning costs, annual costs, the substrate supply, personnel, operational and capital costs all increase as the scale increases. However, the costs per Nm^3 biogas/hour of both raw biogas and upgraded biogas decrease when the scale increases. There are large differences between cost per kWh of methane for the calorific value and the fuel heating value, they decrease rapidly as scale increases.

Table 8. Cost of biogas upgrading with co-digestion (90% manure and 10% maize silage) (Urban, 2009)

Biogas production, "manure system" substrate mix: 90% manure, 10% renewable resources	Plant capacity Nm ³ / h			
	Property	100	250	500
Investment costs	€	535,100	1.08 million	1,850 000
including mechanical engineering	€	67,000	147,000	252,000
including buildings	€	303,900	619,500	1,080 000
including electrical control	€	51,500	94,500	144,000
Other	€	92,700	189,000	324,000
Decommissioning costs	€	20,000	30,000	50,000
Annual Costs	€/y	217,400	514,100	927,100
Substrate supply (maize silage)	€/y	79,600	199,100	398,200
Personnel costs	€/y	12,800	38,300	63,900
Maintenance	€/y	8,000	16,200	27,800
Electricity	€/y	12,500	31,200	62,400
Heat	€/y	40,800	100,800	154,700
Other	€/y	8,600	17,300	29,600
Capital costs	€/y	55,100	111,200	190,500
Specific Costs				
a) cost per Nm ³ raw biogas	€/Nm³	27.18	25.71	23.18
b) costs per Nm ³ methane	€/Nm³	47.68	45.10	40.66
c) cost per kWh of methane (calorific value) € / kWh	€/kWh	4.78	4.52	4.08
d) cost per kWh of methane (fuel heating value) € /kWh	€/kWh	4.31	4.08	3.68

Table 9 presents the specific costs for a 1,500 Nm³/h or 2,000 Nm³/h which are waived for the installation, since there are no standard variants for this plant available. This table provides information on the costs of water scrubbing by Malmerg. From the table it is clear that investment costs, decommissioning costs, annual costs, the substrate supply, personnel, operational and capital costs all increase as the scale increases. Once more the costs per Nm^3 biogas/hour of both raw biogas and upgraded biogas decrease when the scale increases. There are large differences between cost per kWh of methane for the calorific value and the fuel heating value, they decrease rapidly as scale increases.

Table 9. Cost of carbon dioxide removal using water scrubbing by Malmerg (Urban, 2009)

Water scrubbing Malmberg		Plant capacity Nm ³ / h		
	Property	250	500	1,000
1. Investment costs	€	1,145 000	1,323 500	1,699 000
a) plant	€	900, 000	1,070 000	1,380 000
b) gas treatment	€	200,000	200,000	250,000
c) building costs	€	45,000	53,500	69,000
2. Annual costs	€/y	229,300	326,500	523,100
a) operating costs	€/y	111,400	190,200	348,200
including electricity	€/y	75,000	150,000	300,000
water resources	€/y	300	500	1,000
thermal gas treatment	€/y	6,000	6,000	6,000
b) personnel	€/y	7,200	7,200	7,200
c) maintenance and repair	€/y	22,900	26,500	34,000
d) capital costs		117,900	136,300	174,900
3. Specific costs (purchase of raw biogas)				
a) specific cost per Nm ³ raw biogas	€/Nm³	11.47	8.16	6.54
b) specific costs per Nm ³ methane	€/Nm³	21.63	15.40	12.34
c) specific cost per kWh of methane (Hi, N)	€/kWh	2.17	1.54	1.24
4. Specific costs (production of biogas)	Nm³/h	135	269	539
a) specific cost per Nm ³ gas product	€/Nm³	21.23	15.17	12.13
b) specific costs per Nm ³ methane	€/Nm³	21.85	15.56	12.46
c) specific cost per kWh of methane (calorific value)	€/kWh	2.19	1.56	1.25
d) The specific cost per kWh of methane (fuel heating value)	€/kWh	1.98	1.41	1.13

Table 10 is based on information from the manufacturers and therefore can vary greatly when compared to other manufacturers. This shows an increase in the costs to purchase carbon dioxide removal technologies when the scale of the biogas upgrading plant increases. This table compares amine scrubbing with PSA, it is interesting to note that the prices given are similar for investment costs and most annual costs. However, there are a few differences such as amine scrubbing has a higher cost for heat requirement, whereas PSA has a higher electrical use cost. The benefit here for PSA is that is does not require any heat energy, but does have slightly higher maintenance and capital costs. PSA is the cheapest for the specific costs also.

Table 10. Cost overview of carbon dioxide removal for the company Cirmac, Netherlands (Urban, 2009)

Amine scrubbing. Cirmac 500 Nm ³ / h	Property	Amine scrubbing	PSA
1. Investment costs	€	996,200	1,068 600
a) plant	€	839,000	903,000
b) building costs	€	50,000	50,000
Construction	€	50,000	50,000
commissioning	€	29,500	29,500
equipment replacement	€	27,700	36,100
2. Annual costs	€/y	363,300	338,300
a) operating costs	€/y	260,700	228,300
includes electricity	€/y	72,000	150,000
includes heat	€/y	134,900	0
operating medium	€/y	7,200	6,300
b) personnel	€/y	6,300	8,800
c) maintenance	€/y	40,300	63,200
d) capital costs	€/y	102,600	110,000
3. specific costs			
a) specific cost per Nm ³ raw biogas	€/Nm³	9.08	8.46
b) specific costs per Nm ³ methane	€/Nm³	17.14	15.96
c) specific cost per kWh of methane (H, N)	€/kWh	1.72	1.60
3. Specific costs (production of biogas)	Nm³/h	272	264
a) specific cost per Nm ³ gas product	€/Nm³	16.70	16.02
b) specific costs per Nm ³ methane	€/Nm³	17.15	16.45
c) specific cost per kWh of methane (calorific value)	€/kWh	1.72	16.45
d) specific cost per kWh of methane (fuel heating value)	€/kWh	1.55	1.49

In Table 11 gives the specific costs of the different methods for carbon dioxide separation are compared. This should not be considered the same for all system sizes before the relevant cost data has been calculated. For example, the potential revenues or a heat extraction (applies especially for amine scrubbing, but also for the water scrubber and the pressure swing adsorption) can be taken into account. The economic comparison of the different methods should not be overlooked so that in the chemical scrubbing the product gas pressure, and in all other proceedings under pressure usually between 4 and 7 bar as a standard (Urban, 2009). This table also shows that the averages decrease as the scale increases.

Table 11. Cost comparison of the specifics of carbon dioxide removal (Urban, 2009)

Company		Plant capacity Nm ³ / h				
	Property	250	500	1,000	1,500	2,000
PSA - Carbotech	€	*2.26	1.64	1.31	*1.24	1.20
PSA- Cirmac	€	N.A.	1.65	N.A.	N.A.	N.A.
Water Scrubbing Malmberg	€	2.19	1.56	1.25	*1.23	*1.18
Water Scrubbing Flotech	€	2.52	1.79	1.55	N.A.	N.A.
Amine scrubbing Cirmac	€	N.A.	1.72	N.A.	N.A.	N.A.
Amine scrubbing MT-Energie	€	1.96	1.58	1.35	*1.27	*1.23

N.A. Not available *Estimation

Table 12 presents information on the waste streams including the five main upgrading technologies with and without hydrogen sulphide removal. As part of the cryogenic separation the hydrogen sulphide is removed during this process, whereas for PSA the hydrogen sulphide needs to be removed before the process to avoid damaging the process. This table shows that water scrubbing is the cheapest process for dealing with the waste streams and cryogenics is the most expensive.

Table 12. Upgrading technologies costs with and without hydrogen sulphide removal (de Hullu et al., 2008)

		Water Scrubbing	PSA	Chemical Scrubbing	Membrane Separation	Cryogenic
Without hydrogen sulphide	€ per Nm^3/biogas	0.13	N.A.	0.17	0.12	N.A.
Cost per Nm^3/biogas upgraded	€ per Nm^3/biogas	0.13	0.25	0.28	0.22	0.44

N.A. Not available

5.3 Technical evaluation of biogas upgrading

Table 13 gives the technical results from the questionnaires which form the case studies the results show that even though Kalmari's Farm is a small scale biogas gas upgrading facilities and Kristianstad is large scale there can be both big differences and similarities in the technical properties of the plant. For example, Kalmari's Farm has a lower biomass feed rate than Kristianstad, there is another large difference in the biogas produced per day, the water consumed and the capacity of the cleaning system.

Table 13. Technical information from the raw data

Property	Kalmari's Farm	Kristianstad
Biomass feed rate	15-25 kg/hour	45+ kg/hour
Temperature	Mesophilic	Mesophilic
Organic Loading Rate	N.A	2.5 $kgm^{-3}d^{-1}$
Hydraulic Loading Rate	40 + days	40 + days
Biogas produced per day	1,000 m^3/day	18,000 m^3/day
Methane content	55-65%	50-70%
Water consumed	5 m^3/day	150 m^3/day (approx.)
Capacity of upgrading system	20-30 m^3/hour	30-50 m^3/hour*
Capacity of cleaning system	20-30 m^3/hour	800 m^3/hour
Methane yield of final upgraded biogas	N.A	0.48 CH_4/kg VS
Methane content of upgraded gas	91-100%	91-100%
Methane losses	<2%	<1.5%
Additional cleaning	No	No
Energy consumed	0.9 kWh/ m^3	0.7 kWh/ m^3
Final cost upgraded gas	0.2€	N.A

N.A. Not available

* Note, this is the information given in the questionnaire but it is assumed the answer was misread and it should be 300-500 m^3/hour as Kristianstad is a large scale facility.

Table 14 gives information from Urban (2009) on the different upgrading technologies and the technical parameters. For example, PSA, water scrubbing and physical absorption use the same operational pressures but the methane losses vary from <0.1-<3% which affects economics, the larger the scale the lower the methane losses are desired to be as the more bio-methane is lost in the process. Electric consumption is the same with PSA and water scrubbing which is highest with physical absorption and lowest with chemical absorption.

Finally there is no heat required for PSA and water scrubbing but physical absorption requires moderate extra heat and chemical absorption requires a lot of extra heat.

Table 14. The most common biogas cleaning methods a comparison of purification equipment based on manufacturers information (Urban, 2009)

Parameter	PSA	Water Scrubbing	Physical Absorption	Chemical Absorption	Biosling®
Biogas Pretreatment Required	Yes	No	No	Yes	No
Operating Pressure	4-7 bar	4-7 bar	4-7 bar	N.A	2
Methane Losses	< 3%	<1%	2-4%	<0.1	<2 %
Methane Content	>96%	>97%	>96%	>99%	
Electricity Consumption	0.25 kWh/ Nm^3	<0.25 kWh/ Nm^3	0.25-0.33 kWh/ Nm^3	<0.15 kWh/ Nm^3	N.A.
Heat Requirement	None	None	55-80 °C	160 °C	N.A.
Controllability compared with the nominal load	+/- 10 %	50-100	10-100	50-100	N.A.
Number of facilities (pc)	>20	>20	2	5	N.A.

N.A. Not available

Table 15 gives general information about the five main biogas upgrading technologies. All upgrading technologies have high gas quality but there are differences in gas volume. For example, water scrubbing has a high gas volume, PSA is medium and membrane separation has a low value. It also includes an overview on methane efficiency, emissions and waste streams.

Table 15. Comparison of demands for the most common technologies at large and small scale (Lems & Dirkse, 2010)

	Water Scrubbing	Catalytic Absorption	PSA	Membrane Separation	Cryogenics	Large Scale	Small Scale
Gas Quality	High	High	High	High	High	High	High
Gas Quantity Volume	High	High	Medium	Low	Medium	High	Low
Compact	Medium	Medium	No	Yes	No	Medium	Yes
Methane efficiency	High	High	Medium	Low	High	High	Low
Emissions	Low	Low	Medium	Medium	Low	Low	Medium
Waste streams	Continuous	Continuous	Batch	Batch	Continuous	Continuous	Batch

Green best for small scale, Yellow best for large scale, Blue for both

Then the environmental impacts should be considered such as methane leakage and odour. on how they can affect the process and the surrounding environment.

Methane leakage is important to prevent on any scale as methane is a harmful Greenhouse gas which is 23 times more harmful than carbon dioxide. All areas which produce gas should be sealed within the process parameters and post storage tanks of gas and digestate.

Odour is also another issue for some biogas plants at odour producing times normally coincide with waste deliveries prior to digestion. Filters can be installed to reduce this issue.

The upgrading technologies have between one and two waste streams. Pressure swing absorption and membrane separation just have one waste stream. Chemical absorption and water scrubbing have two waste streams. The amount of waste is also important to be considered. Chemical absorption can be classed as having two waste streams as one contains the used chemicals and the other contains the carbon dioxide. Some waste streams need additional treatment before they can be discharged, for example cryogenic separation waste streams require further treatment (de Hullu et al, 2009)

Lems and Dirkse (2010) state that methane efficiency is the percentage of methane which is converted into upgraded gas. It is of utmost important to large scale plants as a small difference in efficiency means a large difference in output of biogas leading to decreased profits. Lems and Dirkse (2010) give the example of a 0.5% less efficiency at 1000 Nm^3/h means >42.500Nm^3/ year upgraded gas extra = ± 25.000 €. With regards to the small scale plants the change in output is small and the biogas can be easily used for other energy sources such as heat and power generation which keeps the energy efficiency maximal (Lems & Dirkse, 2010)

6 CASE STUDIES

Firstly, the following results are from literature as it was not possible to gather more than two questionnaires from the results received. There results show the costs of the upgrading process themselves rather than at a scale level, it just shows the overall cost of that technology. It is important to know this cost as the efficiency for the technology and the price can be very different.

The following two case studies are from the questionnaires that were designed for this thesis. The questionnaires were designed to target all areas in regards to the costs for the scale of the biogas process, feedstock substrates, technical aspects, economics aspects, operation, maintenance, energy consumption, the costs of upgrading itself and finally the cost of the final upgraded biogas. This information is important so that the final cost of the biogas can be related to the scale of the biogas upgrading plant. These results will be explained in more detail in the discussion section of this thesis.

Case Study 1- Kalmari’s Farm, Leppävesi, Finland:

- Small scale, 40 m^3/h
- Feedstock sources: Agriculture and local municipality
- Feedstock: Energy crops, manure and industrial waste
- Biomass federate: 15-25 kg/hour
- Mesophilic reactor
- Organic loading rate: not currently known
- Hydraulic loading rate: 40+ days

Biogas Production:

- 1,000 m^3/day
- Methane content 55-65%
- End use: CHP, Upgrading, heating and drying crops
- Uses for upgraded fuel: vehicle fuel, sold on site
- Water consumption: 5 m^3/day

Upgrading system:

- Water scrubbing
- Upgrading capacity: 20-30m^3/hour
- Yield final gas: not known (methane)
- Methane content of upgraded gas: 91-100%
- Methane losses <2%

Energy:

- Amount of compressors: 0-3
- Power 5.5 kW/hours
- Additional cleaning required: No
- Type of cleaning technology: Water absorption, high pressure by activated carbon or molecular sieve
- Hydrogen sulphide removal: physical adsorption
- Ammonia removal: No
- Removal of particulates: Desiccant dryer particle filter
- Energy used: 0.9 kWh/ m^3 to pressurize to 270 bar
- Cleaning technology capacity: 20-30 m^3

Economics:

- Final cost of upgraded biogas per m^3: 0.2€
- Capital costs:
    - Upgrading equipment: €250,000
    - Installation and odour control: €30,000
    - Feed compressor €20,000
- Operating costs:
    - Maintenance and personnel: €500 per month

  - Energy: €600 per month
- Methane recovery: 98%
- Energy output: 800 MWh or 2880 GJ/year
- No loan rate/no loan

Case Study 2- Kristianstad Biogas AB, Färlöv, Sweden

- Large scale production, 600 Nm^3/hour
- Feedstock sources: Agriculture, local municipality and industry
- Feedstock: Food waste (MSW fraction), manure, industrial wastes and domestic organic wastes.
- Biomass federate: 45+ kg/hour
- Mesophilic reactor
- Organic loading rate: 2.5 kg $m^{-3}d^{-1}$
- Hydraulic loading rate: 40+ days

Biogas Production:

- 1,800 m^3/day
- methane content 50-70%
- End use: Upgrading and heating
- Uses for upgraded fuel: vehicle fuel
- Water consumption: 150 m^3/day (approximately)

Upgrading system:

- Water scrubbing
- Upgrading capacity: 30-50 m^3/hour
- Yield final gas: 0.48 CH_4/kg VS (methane)
- Methane content of upgraded gas: 91-100%
- Methane losses 1.5% approximately

Energy:

- Gas transported by: pipelines
- Amount of compressors: 0-3
- Power 170 kW/hours
- Additional cleaning required: No

- Type of cleaning technology: activated carbon or molecular sieve
- Hydrogen sulphide removal: biological treatment
- Ammonia removal: No
- Removal of particulates: Filter
- Energy used: 0.7 kWh/ m^3
- Cleaning technology capacity: 800 m^3 /hour

Economics:

- Final cost of upgraded biogas per m^3: Unknown
- Capital costs:
    - Upgrading equipment: around € 1,800 000 (17 million SEK)

Case Study 3. BioSling®, Vittangi, Sweden.

BioSling® has been designed for use on small scale biogas upgrading systems. The BioSling® is composed of a coil of spiraled hoses which is the way in which carbon dioxide is removed from the biogas (BioSling® Brochure, 2011).

The biogas and water are fed alternately into the outermost turn of the coil at a pressure of about 2 Bar. The rotating of the coils means that water and gas will come into close contact with each other. The carbon dioxide is easily absorbed by water. “As the coil rotates, water columns will be forced inward and compress the gas in between” (BioSling® Brochure, 2011). The gas being compressed results in the absorption of the carbon dioxide. When the water and the gas leave the rotating coil at the centre of the coils most of the carbon dioxide is absorbed by the water. The purity of the methane is around 94%. “Only a very small amount of methane is soluble in water. The coil pump is turned slowly so that water and gas flow gently through the hoses and therefore the pumping and compressing processes work very efficiently. As the simple rotating coils replace pumps, compressors and gas-water mixers, a lot of mechanical maintenance is minimised when compared to traditional water scrubbing technology” (BioSling® Brochure, 2011) (Figure 17.).

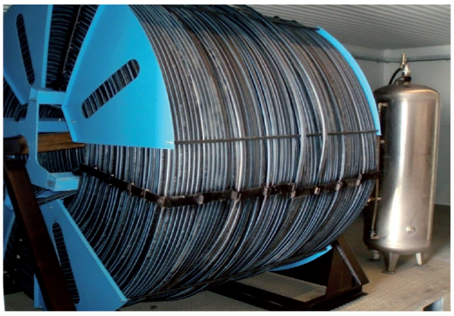

Figure 17. BioSling® coils (BioSling® Brochure, 2011).

The "BioSling® is therefore equipped with a final upgrading step, which removes about half of the carbon dioxide left in gas downstream outlet of the coils to reach the specifications. The final step is a traditional scrubber column. Water enters the column just below its top and falls down in a cascade of many small waterfalls. Gas from the first upgrading step enters at the bottom and raises upwards through the water cascade so that most of the carbon dioxide is captured. At the top outlet the methane gas content has reached the demanded level of 97%. From the bottom of the columns flows water saturated by carbon dioxide" (BioSling® Brochure, 2011) (Figure 18.).

The carbon dioxide is then dissolved by the circulating water must be released to the atmosphere to create a closed circuit. This is achieved by depressurising the water which allows the carbon dioxide to be released from the water; the gas is "flashed". "To enhance flashing the water is poured through a tower, a stripper tower, and air is blown into the pouring water as it falls downward. From the bottom of the tower the clean water is returned to a storage tank by a pump" (BioSling® Brochure, 2011).

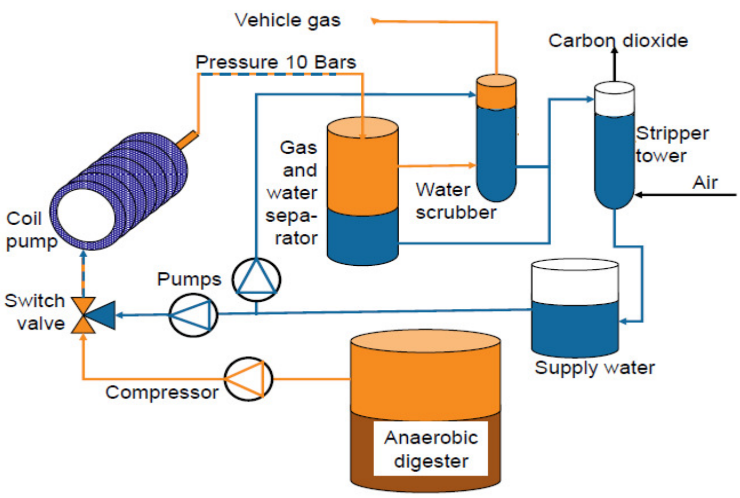

Figure 18. BioSling® Process, flow diagram (BioSling® Brochure, 2011).

The information in Table 16, shows two tables which were given in the BioSling® brochure which gives information about the technical process of BioSling®. It is a useful table with information about the amount of coils and the efficiency, even includes an estimate including the amount of cows or animals which the owner could have and the size of the BioSling® plant that could be installed.

Table 16. BioSling® information (BioSling® Brochure, 2011).

Number of coils	Property	4	8	16
Raw gas capacity (at 65% CH_4, 35% CO_2)	Nm^3	456	912	1,728
Vehicle gas (CBG) capacity/day (8 bar pressure >97 % CH_4)	Nm^3	280	560	1,123
Value at 1.12€/ Nm^3 per day	€/day	314	627	1,258
Diesel compared to CBG 1 Nm^3 = 1 litre diesel	litres/day	280	560	1,123
Suitable dairy farm size (number of cows estimate)	Number of cows	125	250	500
Electricity consumption kWh/day	kWh	112	196	280
Electricity consumption kWh/ Nm^3	kWh	0.40	0.35	0.20

7 DISCUSSION

Overall, this shows that biogas upgrading is feasible but there is limited data available for economic information and some technical information. There are no large scale plants which use cryogenic or biological treatment as an upgrading technology. The type of upgrading technology selected depends on the highest purity that can be achieved.

The factors which are affected by economics are the investment, operating and maintenance costs. There are also technical factors which influence the placement of biogas upgrading plants such as the demand for heat and power generation, an existing facility that produces large amounts of heat that could be utilised by the biogas process. It is also possible that the type of upgrading technology selected is based upon the location and availability of the biogas upgrading manufacturers. Manufacturers claim that methane loss depends on operating conditions (Ahonen, 2010).

From an economic view point large scale biogas upgrading plants are the most profitable. It is also not economically feasible for biogas plant smaller than 150 Nm^3/hour to injection into the grid or for commercial fuel stations. On the other hand, for small scale plants the lowest amount of gas that can be produced with the upgrading plant being economically viable is 20-25Nm^3/h of upgraded gas. Even with this in mind, small scale plants are still the most common in Europe.

Small scale biogas plants are not feasible for gas. However, some small scale plants can be run profitably running as vehicle filling stations and as small CHP plants to supply the plants neighbours with heat and power, Kalamari's Farm, Finland is an excellent example. The problem with small scale operation is they have higher investment and maintenance costs larger systems are more efficient even though there are more parts to maintain.

In calculating the capital cost of the biogas plants a depreciation period of 15 years were assumed, although the depreciation period for the biogas plant equipment such as the fermenter is 16 years and 20 years for the substrate bearing equipment. All the calculations are, however, generally 15 years as an amortization period assumed in order to provide a uniform accounting. The annual costs are therefore somewhat higher than is required for depreciation (Urban, 2009).

PSA is the second most expensive technology according to de Hullu et al. (2008) even so it is one of the most popular technologies used alongside water scrubbing and chemical scrubbing. There are not many cryogenic plants probably as they are the most expensive to build and maintain. Interestingly, regardless of the selected biogas upgrading technology's cost, the larger the plant size the cheaper the cost of production for the upgraded bio-methane. Plant must be closed for maintenance once a year.

Countries which have successfully implemented the use of biogas upgrading technologies have been effectively introduced by policies which favour the use of biomethane. For example, in Sweden they introduced policy that decreases taxes and introduced a special subsidy where a carbon dioxide tax was introduced.

Legislation although not mentioned in this thesis plays an important role into the uptake of biogas upgrading technology. Policy and legislation changes are required at both national (EU and county) and regional levels in order for biogas upgrading technologies to be more economically viable. In regards to policy, some improvements would be the standardisation for the quality aspects and access rights within Europe for injecting the biogas into the gas grid, a wide range of gas quality policy on new gas appliances, the demonstration and implementation projects at various scale sizes where an increased value of biogas and a higher usage rate can be realised. The use of tax and incentives are not unified across Europe, this should be changed by member states as it is in the states interest to increase the use of biomass use to produce vehicle fuel, heat and power.

The major problem for the gathering of raw results for this study was the availability of the information, even after designing the questionnaire and sending it to 50 biogas plants there were only two responses. This was no large enough to give the comparison options for the questionnaire or even to run any statistical tests with. There is also very little data published in peer-reviewed sources on the economics of biogas upgrading.

Further Recommendations

The recommendations for further study would include:

- Research other feedstock options and their feasibility
- Proximity of biogas plants to allow high output to meet supply and demand
- Further information into the exact economics of these plants
- Work out exact carbon footprints for the processes
- Assess the optimal working conditions for all of the processes

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APPENDICES

Questionnaires

Biogas Upgrading Questionnaire Enkät angående uppgradering av biogas

Thank you for taking the time to read and fill out this questionnaire and helping me complete my master's thesis with valuable information. Please delete the inappropriate answers and highlight which bullet points apply. Thank you. (Engish)

Tack för att Ni tar er tid med att läsa igenom och fylla i denna enkät. Det bidrar med viktig information till min masteruppsats och hjälper mig att färdigställa den. Vänligen radera de inkorrekta svaren och stryk under de punkter som gäller. Tack på förhand! (Svenska/Swedish)

This thesis work is part of the EU FP7 project: Valorisation of Food Waste to Biogas

FP7- Energy 2009-1 Grant 241334

Please visit project website: http://www.valorgas.soton.ac.uk/index.htm

Detta examensarbete är en del av EU FP7 projektet: Tillvaratagande av matavfall till biogas
FP7-Energi 2009-1 Grant 241.334
Besök gärna projektets hemsida: http://www.valorgas.soton.ac.uk/index.htm

Name & Address of the biogas plant/Biogas Upgrading unit Namn & adress biogasanläggningen / Biogas Uppgradering enheten

……………………………………………………………………………………………
…………………………………………………………………………..
……………………………………………………………………………………………
………………………………………………………………………….

Do you consent to this information being used for the EU FP7 Valorgas project to be published? Har samtycker du till denna information används för EU-FP7 Valorgas projekt som skall publiceras?

- ☐ Yes Ja
- ☐ No Nej

Technical Issues Tekniska frågor

1. What is the source of the feedstocks for your biogas plant? Vad är källan till ursprungsmaterialet? Varifrån kommer ursprungsmaterialet?

- ☐ Industry Industri/n
- ☐ Agriculture Jordbruk/et
- ☐ Local Municipality Kommunen, alt. det lokala samhället
- ☐ Other…. Övrigt…

2. What is the size of the biogas plant? Vad är storleken på verket/fabriken?

- ☐ Small scale (<100m^3)? Litet <50m3/time alt /h

- ☐ Medium scale (100-200m^3)? Medelstort
- ☐ Large scale (>250m^3)? Stort
- ☐ Other……………… Övrigt…

3. What are the substrates? Vad är råvaror?
   - ☐ Energy Crops Energigrödor
   - ☐ Food waste (MSW fraction) matavfall (MSW fraktioner)
   - ☐ Manure Gödsel
   - ☐ Sewage Sludge Avloppsslam
   - ☐ Waste waters Spillvatten
   - ☐ Industrial wastes Industriavfall
   - ☐ Domestic organic waste Organiskt hushållsavfall

4. What is the biomass feed rate? Vad är inmatningstakten för biomassan?
   - ☐ less that 3kg/hour mindre än 3 kg/timme
   - ☐ 5-9kg/hour 5-9 kg/timme
   - ☐ 10-15kg/hour
   - ☐ 15kg-25kg/hour
   - ☐ 25-45kg/hour
   - ☐ 45kg/hour +

Process Conditions Processförutsättningar

1. What is the temperature range used? Vilket temperaturspann används?
   - ☐ Mesophilic 30-40^{o}C mesofil
   - ☐ Thermophilic 45-60 ^{o}C termofil

2. What is the Organic Loading Rate? Vad är hastigheten för matning av organiskt material?

……………………… kgm^{-3} d^{-1} or VS

3. What is the Hydraulic Loading Rate? Vad är den hydraliska matningshastigheten?
   - ☐ Less than 15 days mindre än 15 dagar
   - ☐ Between 15-20 days mellan 15 till 20 dagar
   - ☐ 15-25 days dagar
   - ☐ 15-30 days dagar
   - ☐ 15-40 days dagar
   - ☐ 40+ days dagar

Biogas Production Biogasproduktion

1. How much biogas is produced per day? Hur mycket biogas produceras per dag?

……………………………… M^3/day /dag

2. What is the methane content? Hur stor är metankoncentrationen?
   - ☐ 30-50%
   - ☐ 50-70%

- ☐ 70-89%
- ☐ 90+%

3. What is the end use for the gas produced? Vad är användningsområdet för den gas som produceras?
   - ☐ CHP
   - ☐ Upgrading
   - ☐ Other Övrigt

4. If other, what is it? Om övrigt, vad i så fall?

………………………………..

5. What are the uses for the upgraded biogas? Vad är användningsområdena för den uppgraderade biogasen?
   - ☐ Injection to the gas grid Tillförsel/till gasnätet
   - ☐ Vehicle fuel Fordonsbränsle
   - ☐ Heat Värme
   - ☐ Heat and Electric production Produktion av värme och elektricitet
   - ☐ Chemical Industry uses Inom den kemiska industrin
   - ☐ Other Industrial uses Övriga användningsområden inom industrin

6. How much water is consumed per day? Hur mycket vatten används per dag?

Total tap water consumption: .... m3/day Total vattenkonsumtion…./dag

Upgrading System Uppgraderingssystem

1. What kind of upgrading system? Vilken slags uppgraderingssystem är det?
   - ☐ Pressure Swing Adsorption
   - ☐ Water Scrubbing (Absorption)
   - ☐ Physical Absorption with organic solvents Fysisk absorption med organiska lösningsmedel
   - ☐ Chemical Absorption with organic solvents Kemisk
   - ☐ High Pressure Membrane Separation Högtrycksmembranseparation
   - ☐ Low Pressure Membrane Separation Lågtrycksmembranseparation
   - ☐ Cryogenics

2. What is the capacity of the upgrading system? Vad är kapaciteten för uppgraderingssystemet?
   - ☐ 0-5 m3/hour
   - ☐ 5-10m3/hour
   - ☐ 10-20 m3/hour
   - ☐ 20-30 m3/hour
   - ☐ 30-50 m3/hour
   - ☐ more than 50 m3/hour mer än …./timme

3. What is the methane yield of the final upgraded gas? Vad är metanutbytet (avkastningen) i den slutligt uppgraderade gasen?

………………………..CH_4/Kg VS

4. What is the methane content of the final upgraded gas? Vad är metaninnehållet i den slutligt uppgraderade gasen?

- ☐ 50-60%
- ☐ 61-70%
- ☐ 71-80%
- ☐ 81-90%
- ☐ 91-100%

5. What are the methane losses? Vad är metanförlusten?

……………………………….%

6. How is the gas transported? Hur transporterasgasen?

- ☐ Pipelines i gasledning/pipeline
- ☐ Tanker i tankbil
- ☐ Other på övrigt sätt

7. If other, then how is the gas transported? Om gasen transporteras på övrigt sätt, hur transporteras den då?
…………………………………………………………

Energy Energi

1. How many existing compressors are there? Hur många befintliga kompressorer finns det?

- ☐ 0-3
- ☐ 3-5
- ☐ 5-10
- ☐ 10+

2. What is there power? Vad är deras effekt?

…………………….. kW/hours /timme

3. Is any additional cleaning required? Behövs ytterligare rengöring?

- Yes/No Ja/Nej

4. What kind of cleaning technology is used? Vad för slags rengöringsteknik används?

- ☐ Water Removal Borttagande av vatten
- ☐ Activated carbon or molecular sieves aktivt kol eller molekylsåll (molekylära filter?)
- ☐ Cooling to condensate kylning till kondensering
- ☐ Water scrubbing vattenskrubbning

Hydrogen Sulphide Removal borttagande av vätesulfat

- ☐ Precipitation

- ☐ Adsorption with activate carbon adsorption med aktivt kol
- ☐ Chemical Adsorption kemisk adsorption
- ☐ Physical Adsorption fysisk adsorption
- ☐ Biological treatment biologisk behandling

- ☐ Ammonia Removal? Yes/No Borttagande av ammoniak? Ja/nej
- ☐ Removal of particulates? Borttagande av partiklar

5. How much energy is consumed? Hur mycket energi åtgår?
…………… Kwh/m^3
6. What is the capacity of the cleaning technology? Vad är kapaciteten för rengöringsteknologin?
…………………………

Economics Ekonomi
1. What is the final cost of the upgraded biogas per m3? Vad är den slutliga kostnaden för den uppgraderade biogasen per m3?
- ☐ 0.01-0.20€
- ☐ 0.21-0.30€
- ☐ 0.31-0.40€
- ☐ 0.41-50€
- ☐ 0.51-0.75€
- ☐ 0.76-1.00€
- ☐ 1.01-2€

2. What was the capital cost to build the plant for? Vad var kapitalkostnaden för att bygga verket/fabriken? Alt. vad kostade det att bygga verket/fabriken?
- Upgrading equipment......................... € Förnyelse av utrustning
- Installation and odour control ……………..€ Installation och luktkontroll
- Feed Compressor ……………………………€ Matningskompressor
- Injection……………………€ tillförsel

3. What are the operating costs? Vad är driftskostnaderna?
- Maintenance…………………..€ Underhåll
- Energy……………………………..€ Energi
- Personnel………………………€ Personalkostnader
- Scrubber…………………………€ Rengöring

4. What is the cost of the process? Vad är kostnaden för processen?
- Methane recovery……………….% Återvinning av metan
- Energy output…………………. GJ/year Energiproduktion /år
- Loan amount……………………………………€ Summa lån
- Interest rate……………………………% Ränta
- Amortization time……………………………years Amorteringstid…år

Reply 1

Biogas Upgrading Questionnaire Enkät angående uppgradering av biogas

Thank you for taking the time to read and fill out this questionnaire and helping me complete my master's thesis with valuable information. Please delete the inappropriate answers and highlight which bullet points apply. Thank you. (Engish)

Tack för att Ni tar er tid med att läsa igenom och fylla i denna enkät. Det bidrar med viktig information till min masteruppsats och hjälper mig att färdigställa den. Vänligen radera de inkorrekta svaren och stryk under de punkter som gäller. Tack på förhand! (Svenska/Swedish)

This thesis work is part of the EU FP7 project: Valorisation of Food Waste to Biogas

FP7- Energy 2009-1 Grant 241334

Please visit project website: http://www.valorgas.soton.ac.uk/index.htm

Detta examensarbete är en del av EU FP7 projektet: Tillvaratagande av matavfall till biogas

FP7-Energi 2009-1 Grant 241.334

Besök gärna projektets hemsida: http://www.valorgas.soton.ac.uk/index.htm

Name & Address of the biogas plant/Biogas Upgrading unit Namn & adress biogasanläggningen / Biogas Uppgradering enheten

Kalmarin Maatila
Vaajakoskentie 104
41310 Leppävesi

Do you consent to this information being used for the EU FP7 Valorgas project to be published? Har samtycker du till denna information används för EU-FP7 Valorgas projekt som skall publiceras?

- ☐ Yes Ja

Technical Issues Tekniska frågor

1. What is the source of the feedstocks for your biogas plant? Vad är källan till ursprungsmaterialet? Varifrån kommer ursprungsmaterialet?

- ☐ Agriculture Jordbruk/et
- ☐ Local Municipality Kommunen, alt. det lokala samhället

2. What is the size of the biogas plant? Vad är storleken på verket/fabriken?

1000 m3 reactor

3. What are the substrates? Vad är råvaror?

- ☐ Energy Crops Energigrödor
- ☐ Manure Gödsel
- ☐ Industrial wastes Industriavfall

4. What is the biomass feed rate? Vad är inmatningstakten för biomassan?

- ☐ 15kg-25kg/hour

Process Conditions Processförutsättningar

1. What is the temperature range used? Vilket temperaturspann används?

- Mesophilic 30-40°C mesofil

2. What is the Organic Loading Rate? Vad är hastigheten för matning av organiskt material?
Currently not known
3. What is the Hydraulic Loading Rate? Vad är den hydraliska matningshastigheten?
- 40+ days dagar

Biogas Production Biogasproduktion

1. How much biogas is produced per day? Hur mycket biogas produceras per dag?

……………………………around 1000…. M^3/day /dag

2. What is the methane content? Hur stor är metankoncentrationen?
55-65 %

3. What is the end use for the gas produced? Vad är användningsområdet för den gas som produceras?
- CHP Yes
- Upgrading Yes
- Other Heating and crops drying Övrigt

4. If other, what is it? Om övrigt, vad i så fall?
Heating and crops drying
……………………………..

5. What are the uses for the upgraded biogas? Vad är användningsområdena för den uppgraderade biogasen?
- Vehicle fuel Fordonsbränsle

6. How much water is consumed per day? Hur mycket vatten används per dag?

Total tap water consumption: ..5 .... m3/day Total vattenkonsumtion…./dag

Upgrading System Uppgraderingssystem

1. What kind of upgrading system? Vilken slags uppgraderingssystem är det?
- Water Scrubbing (Absorption)

2. What is the capacity of the upgrading system? Vad är kapaciteten för uppgraderingssystemet?
- 20-30 m3/hour

3. What is the methane yield of the final upgraded gas? Vad är metanutbytet (avkastningen) i den slutligt uppgraderade gasen?

……………………Not known…..CH_4/Kg VS

4. What is the methane content of the final upgraded gas? Vad är metaninnehållet i den slutligt uppgraderade gasen?

- ☐ 91-100%

5. What are the methane losses? Vad är metanförlusten?

……………………<2%…………%

6. How is the gas transported? Hur transporterasgasen?
Sold on site (filling station 30 meters from upgrading system)
7. If other, then how is the gas transported? Om gasen transporteras på övrigt sätt, hur transporteras den då?
…………………………………………………………

Energy Energi

1. How many existing compressors are there? Hur många befintliga kompressorer finns det?
   - ☐ 0-3

2. What is there power? Vad är deras effekt?

………………5,5…….. kW/hours /timme

3. Is any additional cleaning required? Behövs ytterligare rengöring?
   - /No

4. What kind of cleaning technology is used? Vad för slags rengöringsteknik används?
Water absorption, high pressure
Water Removal Borttagande av vatten
   - ☐ Activated carbon or molecular sieves aktivt kol eller molekylsåll (molekylära filter?)

Hydrogen Sulphide Removal borttagande av vätesulfat
   - ☐ Physical Adsorption fysisk adsorption

   - ☐ Ammonia Removal? /No Borttagande av ammoniak? Ja/nej
   - ☐ Removal of particulates? Yes, dessicant dryer has particle filter Borttagande av partiklar

5. How much energy is consumed? Hur mycket energi åtgår?
…upgraded and pressurized gas to 270 bar……0,9…… Kwh/m^3
6. What is the capacity of the cleaning technology? Vad är kapaciteten för rengöringsteknologin?
…………………… 20-30 m3 of upgraded gas per hour…….

Economics Ekonomi

1. What is the final cost of the upgraded biogas per m3? Vad är den slutliga kostnaden för den uppgraderade biogasen per m3?
0,2 €/ m3 of upgraded and pressurized gas at 270 bar (electricity, water and maintenance costs)
2. What was the capital cost to build the plant for? Vad var kapitalkostnaden för att bygga verket/fabriken? Alt. vad kostade det att bygga verket/fabriken?
   - Upgrading equipment.. 250 000 € Förnyelse av utrustning

- Installation and odour control 30 000 € Installation och luktkontroll
- Feed Compressor 20 000.€ Matningskompressor
- Injection 0 € tillförsel

3. What are the operating costs? Vad är driftskostnaderna?
   - Maintenance 500.€/month Underhåll
   - Energy……………………600.€/month Energi
   - Personnel included in maintenance € Personalkostnader
   - Scrubber € Rengöring

4. What is the cost of the process? Vad är kostnaden för processen?
   - Methane recovery………………>98 .% Återvinning av metan
   - Energy output………..800 MWh…= 2880 GJ/year Energiproduktion /år
   - Loan amount……………………………None for existing plant……€ Summa lån
   - Interest rate……………………………% Ränta
   - Amortization time……………………………years Amorteringstid…år

Reply 2

Biogas Upgrading Questionnaire Enkät angående uppgradering av biogas

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Besök gärna projektets hemsida: http://www.valorgas.soton.ac.uk/index.htm
Name & Address of the biogas plant/Biogas Upgrading unit Namn & adress biogasanläggningen / Biogas Uppgradering enheten
Kristianstads Biogas AB
Wrangels Alle 4, 291 75 FÄRLÖV,
SWEDEN…………………………………………………………………………………
…………………………………………………………………………………..
………………………………………………………………………………………
…………………………………………………………………………

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- ☐ Yes Ja

Technical Issues Tekniska frågor

1. What is the source of the feedstocks for your biogas plant? Vad är källan till ursprungsmaterialet? Varifrån kommer ursprungsmaterialet?

- ☐ Industry Industri/n
- ☐ Agriculture Jordbruk/et
- ☐ Local Municipality Kommunen, alt. det lokala samhället
- ☐ Other…. Övrigt…

2. What is the size of the biogas plant? Vad är storleken på verket/fabriken?

- ☐ Large scale (>250m^3)? Stort

3. What are the substrates? Vad är råvaror?

  - ☐ Food waste (MSW fraction) matavfall (MSW fraktioner)

- Manure Gödsel
- Industrial wastes Industriavfall
- Domestic organic waste Organiskt hushållsavfall

4. What is the biomass feed rate? Vad är inmatningstakten för biomassan?
   - 45kg/hour +

Process Conditions Processförutsättningar

1. What is the temperature range used? Vilket temperaturspann används?
   - Mesophilic 30-40°C mesofil

2. What is the Organic Loading Rate? Vad är hastigheten för matning av organiskt material?

……………2,5…………. kgm^{-3} d^{-1} or VS

3. What is the Hydraulic Loading Rate? Vad är den hydraliska matningshastigheten?
   - 40+ days dagar

Biogas Production Biogasproduktion

1. How much biogas is produced per day? Hur mycket biogas produceras per dag?

……………………18000…………. M^3/day /dag

2. What is the methane content? Hur stor är metankoncentrationen?
   - 50-70% (68%)

3. What is the end use for the gas produced? Vad är användningsområdet för den gas som produceras?
   - Heating
   - Upgrading

4. If other, what is it? Om övrigt, vad i så fall?

……………………………..

5. What are the uses for the upgraded biogas? Vad är användningsområdena för den uppgraderade biogasen?
   - Vehicle fuel Fordonsbränsle

6. How much water is consumed per day? Hur mycket vatten används per dag?

Total tap water consumption: ...approx 150 (not measured)................ m3/day Total vattenkonsumtion…./dag

Upgrading System Uppgraderingssystem

1. What kind of upgrading system? Vilken slags uppgraderingssystem är det?
   - Water Scrubbing (Absorption)

2. What is the capacity of the upgrading system? Vad är kapaciteten för uppgraderingssystemet?
   - 30-50 m3/hour

3. What is the methane yield of the final upgraded gas? Vad är metanutbytet (avkastningen) i den slutligt uppgraderade gasen?

………approx……0,48 m3…………..CH_4/Kg VS

4. What is the methane content of the final upgraded gas? Vad är metaninnehållet i den slutligt uppgraderade gasen?

- ☐ 91-100%

5. What are the methane losses? Vad är metanförlusten?

Approx 1,5……………………………….%

6. How is the gas transported? Hur transporterasgasen?

- ☐ Pipelines i gasledning/pipeline
- ☐ Other på övrigt sätt

7. If other, then how is the gas transported? Om gasen transporteras på övrigt sätt, hur transporteras den då?
Container (high pressure)………………………………………………………

Energy Energi

1. How many existing compressors are there? Hur många befintliga kompressorer finns det?

- ☐ 0-3

2. What is there power? Vad är deras effekt?

………approx 170…………….. kW

3. Is any additional cleaning required? Behövs ytterligare rengöring?

- No

4. What kind of cleaning technology is used? Vad för slags rengöringsteknik används?
Water Removal Borttagande av vatten

- ☐ Activated carbon or molecular sieves aktivt kol eller molekylsåll (molekylära filter?)

Hydrogen Sulphide Removal borttagande av vätesulfat

- ☐ Biological treatment biologisk behandling

- ☐ Ammonia Removal? No
- ☐ Removal of particulates? Filter

5. How much energy is consumed? Hur mycket energi åtgår?
…approx…0,7……… Kwh/m^3
6. What is the capacity of the cleaning technology? Vad är kapaciteten för rengöringsteknologin?
800 m37h…………………………

Economics Ekonomi

1. What is the final cost of the upgraded biogas per m3? Vad är den slutliga kostnaden för den uppgraderade biogasen per m3?
    - No answer

2. What was the capital cost to build the plant for? Vad var kapitalkostnaden för att bygga verket/fabriken? Alt. vad kostade det att bygga verket/fabriken?
    - Upgrading equipment........approx 17 MSEK. For upgrading in 2006...............

3. What are the operating costs? Vad är driftskostnaderna?
    - No answer

4. What is the cost of the process? Vad är kostnaden för processen?
    - No answer