Baltic Biogas Bus

WP3.6 Biogas as a vehicle fuel in commuter buses – Life cycle cost and green house gas study

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The Baltic Biogas Bus project will prepare for and increase the use of the eco-fuel Biogas in public transport in order to reduce environmental impact from traffic and make the Baltic region a better place to live, work and invest in.
The Baltic Biogas Bus project is supported by the EU, is part of the Baltic Sea Region programme and includes cities, counties and companies within the Baltic region.

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Abstract

Biofuels in the transport sector are believed to be capable of reducing the growth in carbon dioxide (CO_2) emissions. The European Union is strongly promoting biofuels, e.g. by an ambitious target of 10 % substitution of transport fuels by renewable energy by 2020.

The aim of this master's thesis was to evaluate the costs and greenhouse gas emissions from the generation, distribution and usage of upgraded biogas in transportation buses. The costs were covered using life cycle cost analysis. The greenhouse gas emissions were based on the literature results of the Life Cycle Assessment analysis. The costs from commuter buses using biogas were compared to buses using diesel. The emissions from diesel and natural gas buses were compared, and the costs were expressed as a specific cost with units €c per driven kilometre (€c/km) and the greenhouse gas emissions as a specific emission with units of carbon dioxide equivalent grams per kilometre (g CO_2eq/km).

A comparative cost estimate was made for the biogas generation capacity of 1 000 Nm^3/h raw gas. The results show that the costs of biogas generation for fuel filling was about 49 €c/km. Respectively, the cost from diesel fuel was 45 €c/km. The specific cost for a gas-powered bus was on average 70 €c/km and respectively for diesel 59 €c/km. The total cost of biogas use as a vehicle fuel was thus 14 % higher than diesel use. Cost calculations were updated from year 2010 to 2012 and during that time diesel price was increased 40 %. Results from update showed that diesel bus costs were placed to equal level with gas buses to 127 and 126 €c/km.

The greenhouse gas emissions from biomethane production were strongly dependent on the used substrate. The driving time greenhouse gas emissions (tank-to-wheel) from a biomethane powered bus were 0 g CO_2eq/km. Total savings of greenhouse gas emissions from biomethane made from manures is about 82 % and 73 % if made from municipal waste.

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I like to thank all my colleagues for providing good working facilities and specially I like to thank Senior Research Scientist Mona Arnold for instructions and supporting comments.

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Tuula Kajolinna

List of abbreviations

CO	Carbon monoxide
CO_2	Carbon dioxide
EEV	Enhanced environmentally friendly vehicle, emissions limits between Euro 5 and 6
HC	Hydrocarbons
NOx	Nitrogen oxides (NO and NO_2)
CBG	Compressed Biogas
kWh	Kilo Watt-hours
GWh	Giga Watt-hours
TWh	Tera Watt-hours
LNG	Liquefied Natural Gas
M€	Millions of Euro
MNm^3	Millions of Normal Cubic meters
TBM	Tertiary-butylmercaptane
THT	Tetrahydrotiophene
Wobbe-index	Indicator of the interchangeability, MJ/Nm^3
€c	Euro cent, 0.01 €
k€	1 000 Euros
g CO_2eq	Carbon dioxide equivalent grams
g CO_2eq/km	Carbon dioxide equivalent grams per kilometre
WTW	Well-To-Wheels: the integration of all steps required to pro-duce and distribute a fuel (starting from the primary energy resource) and use it in a vehicle
TTW	Tank-To-Wheels: description of the burning of a fuel in a vehicle
WTT	Well-To-Tank: the cascade of steps required to produce and distribute a fuel (starting from the primary energy resource), including vehicle refuelling
PSA	Pressure Swing Absorption
LCA	Life Cycle Analysis
SCR	Selective Catalyst Reduction
EGR	Exhaust Gas Recirculation
TWC	Three-Way Catalyst
DPF	Diesel Particle Filter
EURO V	European standards limiting certain non-CO_2 emissions (CO, C, NO_X, PM) in exhaust gases in vehicles
RES	Directive of the European Parliament and of the European Council on the Promotion of the Use of Energy from Re-newable Sources, 2009/28/EC
VTT	VTT Technical Research Centre of Finland

1 Introduction

Biofuels in the transport sector are believed to be capable of reducing the growth in carbon dioxide (CO_2) emissions, which supports the commitment of the European Union to fulfilling the requirements of the Kyoto Protocol. The European Union is strongly promoting biofuels, e.g. by an ambitious target of 10 % substitution of transport fuels by renewable energy by 2020. Biofuels can be, for example, ethanol or biogas made from crops or wastes.

This study was conducted for the BalticBiogasBus project which was included in the Baltic Sea Region programme funded by the European Union. The aim of the project was to generate strategies and policies to introduce biogas as well as to analyse necessary measures in biogas production, distribution and bus operations. Biogas can be used as natural gas after biogas upgrading. There were 12 partners from 8 countries in the Baltic region directly involved in the project. The project partners were Stockholm Public Transport (SL), Biogas East, Ruter, Hordaland Oil and Gas (HOG), Skyss, the Technical Research Centre of Finland (VTT), Tartu, Riga City Council Traffic Department, Kauno Autobusai, Motor Transport Institute (MTI), ATI erc GmbH, and the Innovation and Trend Centre (ITC). (BalticBiogasBus 2010)

1.1 Aims of the assessment

The aim of this master's thesis was to assess the costs and greenhouse gases from the generation, distribution and usage of biogas in transportation buses. The assessed costs were covered using life cycle cost analysis. The greenhouse gas emissions were based on literature results of Life Cycle Assessment analysis. The study covered the life cycle costs and impacts for biogas generation, upgrading, distribution to filling stations, filling stations and usage in buses. Since the technology of biomethane-driven vehicles is exactly the same as for vehicles fuelled with natural gas, the costs and emissions were estimated using natural gas. The costs of bus usage included bus investments, after-treatment, fuel and maintenance. The costs were compared to diesel and natural gas usage. An emissions comparison was made between natural gas buses and diesel buses.

The costs of biogas utilization as a vehicle fuel were calculated for a raw gas flow of 1 000 Nm^3/h. Figure 1 shows the separate processes of the life cycle cost and the greenhouse gas assessments. The processes cover the so-called Well-to-wheel (WTW) chain, which comprises production of the fuel, bringing it into the fuel storage of the vehicle and the end-use phase.

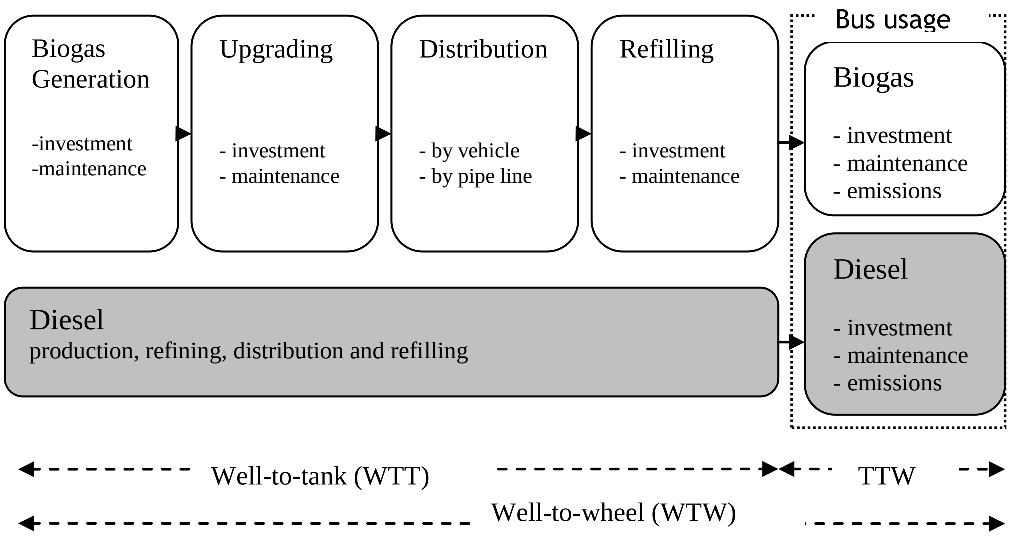

Figure 1. Separate parts of the well-to-wheel chain.

1.2 *Limitations*

This assessment focused on digested biogas. The costs and emissions of the substrate before digesting were excluded. The resale value and emissions caused by the digestate were also excluded because these factors are strongly dependent on the land applications, quality of the digestate, country policy, etc. The costs of diesel and natural gas refining and distribution were not broken down, and only the resale prices were used for the cost comparison.

1.3 *Definition of the functional units*

The functional units are presented per vehicle mileage. The costs are presented as €c/km and the greenhouse gas emissions as grams CO_2eq/km. The driving time emissions are presented as g/km. The fuel consumption values are based on the results from measurements with the German Braunschweig city bus cycle made by VTT.

The calculations are based on the following values and calculation principles;

- The methane content of 60 % was used in raw biogas. In upgraded biogas, called biomethane, the methane content of 97 % was used. Therefore the raw gas flow of 1 000 Nm^3/h equals 620 Nm^3/h of biomethane according to the calculation: 1000 Nm^3/h * 0.6 / 0.97 = 620 Nm^3/h.

- A density of 0.73 kg/Nm^3 for 100 % methane and density of 0.84 kg/l for diesel were used.
- The fuel consumption for a gas bus was 42.6 kg/100 km. The conversion to Nm^3/km units was calculated as 42.6 kg / 100 km / 0.73 Nm^3/kg / 0.97 = 0.6 Nm^3/km.
- The fuel consumption for a diesel bus was 37.5 kg/100 km. The conversion to l/km units was calculated as 37.5 kg /100 km / 0.84 kg/l = 0.45 l/km.
- The costs from €c/Nm^3 of biomethane was converted to specific cost as €c/km by calculation, e.g. 1 €c/Nm^3 / 0.6 Nm^3/km = 1.67 €c/km.
- Energy content for biomethane of 36 MJ/Nm^3 was used.
- Energy content for diesel of 43.2 MJ/kg was used.
- Greenhouse gas emissions from unit g CO_2eq/MJ were converted to specific emission as g CO_2eq/km by calculating 1 g CO_2eq/MJ * 36 MJ/Nm^3 * 0.6 Nm^3/km = 21.6 g CO_2eq/km.

1.4 Background

The background section presents general information on biogas, utilized amounts of biogas, number of biogas generation plants and number of the natural gas powered buses in the Baltic region.

1.4.1 Biogas in general

Biogas is generated by digesting organic material. In the generation of biogas by anaerobic digestion, a wide range of biomass types can be used as substrates. The most common biomass categories used in European biogas production are animal manure and slurry, agricultural residues and by-products, digestible organic wastes from the food and agro-industries, organic fraction of municipal waste and from catering (vegetable and animal origins), sewage sludge and dedicated energy crops (e.g. maize, miscanthus, sorghum, clover). Also collected landfill gas is called biogas.

The energy contents and compositions of biogases from digesting and landfill are presented in Table 1.

Table 1. Energy contents and compositions of different types of biogas (Persson et al. 2006)

		Digested	Landfill
Energy content	kWh/Nm^3	5.3-7.5	4.4
	MJ/Nm^3	23	16
	MJ/kg	20.2	12.3
CH_4	vol-%	53-70	35-65
CO_2	vol-%	30-47	15-50
H_2O	vol-%	2-7	0-3
Higher hydrocarbons	vol-%	0	0
H_2S	ppm	0-10000	0-600
NH_3	ppm	< 100	5
total chlorine (as Cl^-)	mg/Nm^3	0-5	20-200

Biogas has many energy utilizations, depending on the content of the biogas and the local demands. Generally, biogas can be used for heat production by direct combustion, electricity production by engines or micro-turbines, CHP generation or as a vehicle fuel (Figure 2).

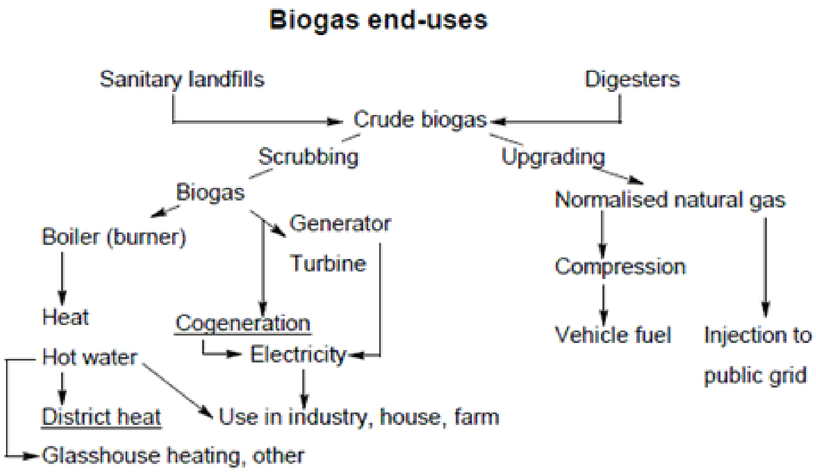

Figure 2. Overview of biogas utilization. Formatted from Al Seadi *et al.* (2008).

1.4.2 Utilization of biogas in the Baltic region

The production of biogas has increased in the Baltic countries between 2007 and 2008. The utilized biogas amounts in the Baltic region in 2007 and 2008 are shown in Table 2.

Table 2. Utilized biogas amounts in 2007 to 2008.

	2007 [1]	2008
	GWh	GWh
Norway[2]	?	480
Germany	26 325	90 000[3]
Poland	692	195 [4]
Finland	405	462 [5]
Sweden	300	1 200 [6]
Estonia	46	55[7]
Lithuania	28	6 [8]
Latvia	0.1[9]	?
Total	~28 000	~92 000

The biogas generation plants and landfill gas collection plants in the Baltic region are listed in Table 3.

Table 3. Biogas reactors and landfill gas plants 2008 or 2009.*

	municipal waste+crops	Landfill	Sewage+manure	Total
Norway [2]	6	41	24	71
Germany [3]	?	?	?	4 000
Poland [4]	3	35	60	98
Finland [5]*	8	33	15	56
Sweden [2]	25	58	144	227
Estonia [9]		5	3	8
Lithuania [10]	5	78	73	156
Latvia[11]		2	1	3
Total				4 619

[1] ER 2008
[2] Nielsen 2010
[3] Gerbio 2009
[4] IEO 2009
[5] Kuittinen 2008
[6] SGC 213
[7] Kasek 2009
[8] Council of Lithuania 2009
[9] Oja, Minek 2010
[10] Council of Lithuania 2009
[11] Dimitrova et al. 2008

The numbers and shares of gas-powered buses in the Baltic region are shown in Table 4.

Table 4. Gas buses in the Baltic region on 2009 (Boisen 2010).

	number	%
Norway	138	4
Germany	1 550	49
Poland	300	10
Finland	95	3
Sweden	963	31
Estonia	0	0
Lithuania	100	3
Latvia	10	0.3
Total	3 156	100

2 Methodology

2.1 Data collection

The data used in this assessment were collected from the Internet and from specialists via email.

2.2 Life Cycle Cost (LCC)

Life Cycle Cost refers to the total cost of ownership over the life. LCC is also called the whole life cost. This assessment is referred to as "well-to-wheel" costs. Generally, the typical areas of expenditure which are included in calculating the life cycle costs are planning, design, construction/acquisition, operations, maintenance, renewal/rehabilitation, financial and replacement or disposal.

In this assessment the yearly capital cost was calculated with 6 % annuity and a payback time of 15 years. The fuel consumption of the gas-powered bus was assumed to be 0.6 Nm^3/km and for the diesel powered bus 0.45 l/km, based on the fuel consumption results presented in Chapter 4.2.1.

The price for diesel fuel of 1 €/litre was used, and thus the specific cost for diesel fuel was 45 €c/km. The specific cost for biomethane fuel was calculated in this assessment to be 49 €c/km. In July 2010, the price for vehicle natural gas in Finland was 1.1 €/kg, which equals 0.80 €/Nm^3 giving the specific cost for fuel of 48 €c/km (Gasum2 2010). Separate calculations using the natural gas price are not presented because the calculated price for biomethane was practically the same.

2.3 Life Cycle Analysis (LCA)

Generally, LCA compares a full range of environmental impacts from producing and using the products. The term 'life cycle' covers the assessment of raw material production, manufacture, distribution, use and disposal including all the intervening transportation steps necessary or caused by the product's existence. The sum of all those steps is the life cycle of the product.

In this assessment, only the greenhouse gases were evaluated. The LCA results were based on the studies made using the ISO 14000 environmental management standards. The LCA analysis covered the greenhouse gas emissions of fuels used for road transportation called “well-to-wheel”, which was broken down into two stages called "well-to-tank" and "tank-to-wheel". The well-to-tank part comprises production of the fuel and bringing it into the fuel storage of the vehicle. Tank-to-wheel describes the end-use phase.

Using a hydrocarbon fuel, whether fossil or biogenic, the exhaust gases contain CO_2. In the case of biofuels, the end-use was considered to be carbon neutral. Therefore, only fossil carbon required to bring the fuel to the fuel tank (well-to-tank) was accounted for.

2.4 Sensitivity assessment

Sensitivity assessment was performed as a critical review of the used data.

3 LCC - Inventory

The inventory section includes basic information and costs for biogas generation, upgrading, distribution types, filling stations and usage in commuter buses.

3.1 Anaerobic digestion

The substrates for digestion can be classified according to various criteria: origin, dry matter content, methane yield, etc. A substrate mix with dry matter content lower than 20% is used for what is called wet digestion, which includes typically animal slurries and manure as well as various wet organic wastes from food industries. When the dry matter content is as high as 35%, it is called dry digestion, and it is typical for energy crops and silages. The choice of types and amounts of substrates for the anaerobic digestion substrate mixture depends on their dry matter content as well as the content of sugars, lipids and proteins. (Al Seadi *et al.* 2008)

The digestion process can take place at different temperatures, divided into two temperature ranges: mesophilic (25 – 45°C) and thermophilic (45 – 70°C). Typical retention times for digestion are with mesophilic 30–40 days and with thermophilic 15–20 days. The thermophilic process is a method used increasingly in biogas plants due to the faster retention time and higher methane content. (Al Seadi et al. 2008)

Depending on the substrate, also hygienization of the digestate must be done. Hygienization is typically done by heating the digestate to 70 °C for one hour after the digestion chamber. Separated hygienization is not needed if thermophilic digestion over a temperature of 52 °C is used. (Lantz, Börjesson 2010)

Figure 3 shows the principle of biogas generation by digesting.

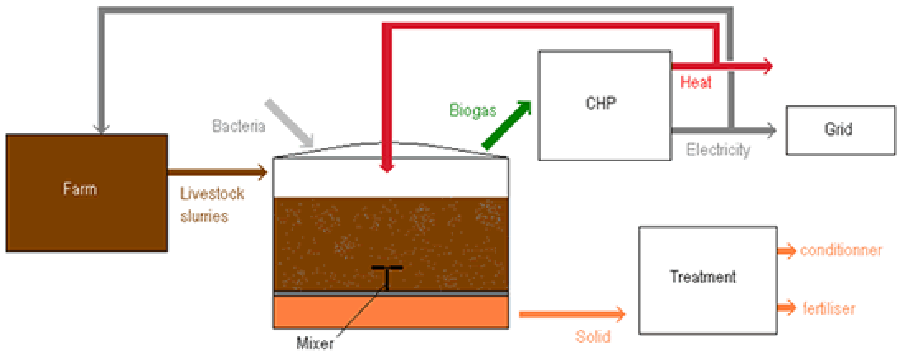

Figure 3. Example of an anaerobic digestion process (County Waterford 2010).

3.1.1 Costs of biogas generation

Investment

The cost of biogas generation depends on the digested substrate, substrate transport distance, chosen digestion technique and the production capacity.

Urban *et al.* (2009) calculated the costs of biogas generation from manure with three capacities and from maize with five capacities. Investment and usage costs were listed, and one conclusion was that the cost of digesting maize with a raw gas capacity of 500 Nm^3/h was 36 % more expensive than digesting manure.

Held *et al.* (2008) listed the investment and operation costs of biogas generation plants in Sweden. The listed costs covered substrates from sewage sludge, pig manure and household waste.

Mårtensson (2007) studied the cost of generation of biogas from different substrates. The costs for upgraded and pressurized gas were as follows: sewage sludge 0.22–0.48 €/Nm^3 (equal to 13–29 €c/km), organic waste 0.55–0.65 €/Nm^3 (33–39 €c/km), crops 0.53–0.74 €/Nm^3 (32–44 €c/km) and manure 0.47–0.95 €/Nm^3 (28–57 €c/km). The cost of compressing gas to a distribution pressure of 4 bar was 0.11 €/Nm^3 (7 €c/km).

According to Jarvis (2009), digestion chambers with a volume of 800 m^3, 1 400 m^3 and 2 000 m^3 cost 480 k€, 560 k€ and 700 k€, respectively.

According to Jarvis (2009), the investment costs of gas drying with a freezing system costs 8 000–10 000 €, with an absorption system 5 000–10 000 € and with a pressuring system 30 000–50 000 €. The cost of a hygienization unit for a 2 000 m^3 digestion chamber plant is 100 000 €.

Based on the listed figures above, the calculated investment costs of biogas generation versus capacity are shown in Figure 4. Details are given in Appendix 1.

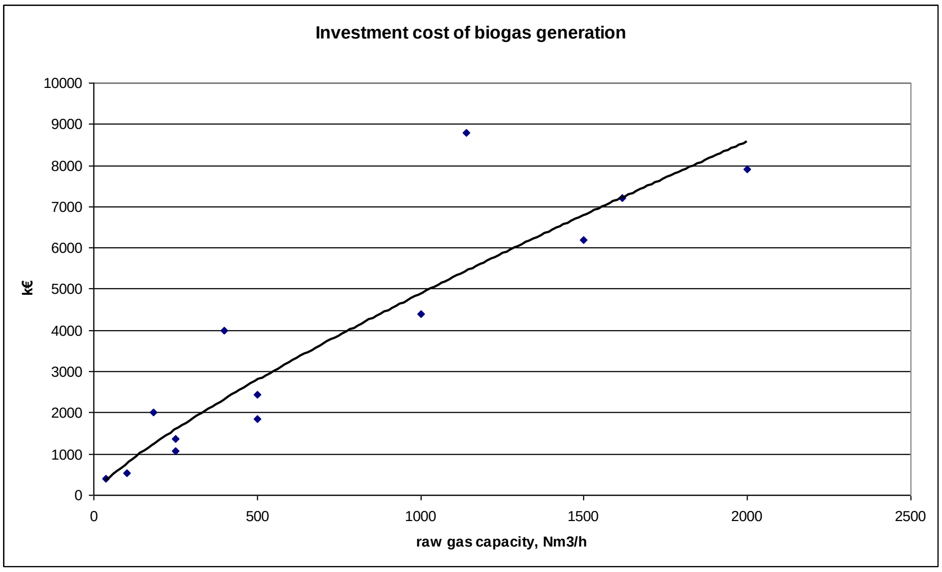

Figure 4. Investment cost of biogas generation.

Operation

According to Urban *et al.* (2009), for manure digestion the yearly maintenance costs are 1.5 % of the total investment costs of biogas production. The total yearly costs are distributed as follows: substrate 37–43 %, personnel 6–8 %, maintenance 3–4 %, electricity 6–7 %, heating 17–20 %, others 3–4 %, and capital 20–25 %.

According to Forsberg (2009), the yearly labour/personnel cost was 8 % and the maintenance 6 % of the total investment costs of biogas production. The total yearly maintenance costs were 14 % of the investment costs, and therefore it was 0.34 – 0.51 €/Nm^3 (20–31 €c/km) for biomethane.

Jarvis (2009) estimated the annual costs of biogas generation plants. The reported results showed the usage cost of 37 % and maintenance costs of 12 % of the total annual capital costs. It was also reported that the annual costs calculated by one system manufacturer were for usage 46–50 % and for maintenance 2.5 %. According to one operator, the usage costs correspond to 50–100 % of the total annual capital costs.

According to Kalmari (2006), the yearly usage costs can be estimated with the formula 1 000 € + 1 €/MW of needed heating energy. The maintenance and energy production costs can be estimated using the formula MW_{fe} *15 €/MW electricity consumption.

The investment cost for separated process heating, heat pump, sludge heat exchangers, etc. for a raw gas capacity of 750 Nm^3/h was 1.25 M€ in Bekkelaget in Norway (Björkman 2010).

The investment and operational cost data given above were used to calculate the specific costs versus raw gas capacity. The fuel consumption for a gas bus of 0.6 Nm^3/km was used in the calculations. Different substrates were not separated in the calculations. The results from the calculations made are shown in Figure 5. Also the cost results obtained by Mårtensson and by Lantz and Börjesson are shown in the figure for comparison and these results are not bound to any capacity data. The costs given by Mårtensson are estimated for upgraded and pressurized biomethane, and thus the results are not directly comparable with the calculated results and the results given by Landz and Börjesson. Details of the calculated results are given in Appendix 1. The usage costs were calculated according to Jarvis (2009) as 50 % of the yearly capital cost, if the exact data was not available. The trend line fitted into the picture is a so-called power trend line of the calculated results.

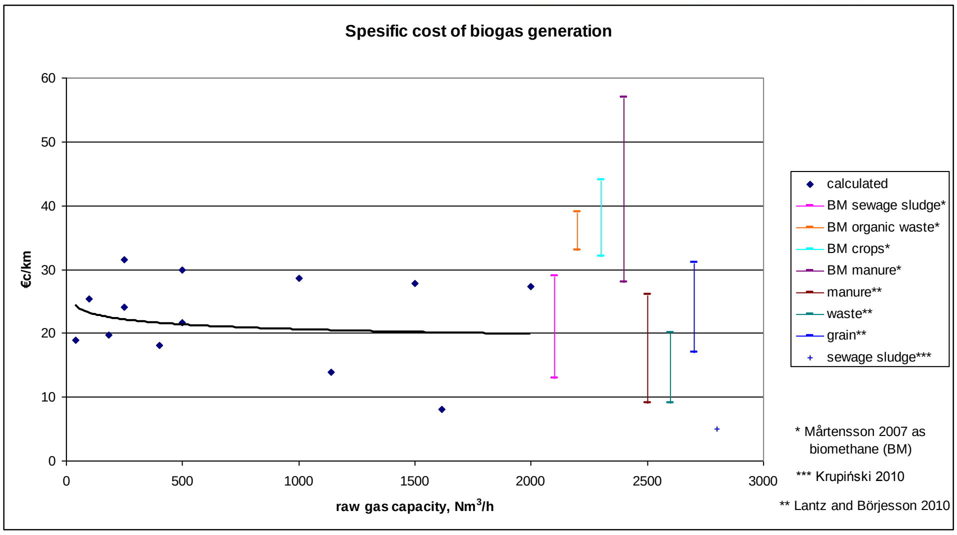

Figure 5. Specific costs of biogas generation.

Lantz and Börjesson (2010) reported that the digestion cost of manure was 0.15–0.45 SEK/kWh (equal to a specific cost of 9–26 €c/km), waste 0.15–0.35 SEK/kWh (9–20 €c/km) and grain 0.3–0.55 SEK/kWh (17–31 €c/km).

In Poland the price of 1 m^3 of biogas was estimated in the beginning of January 2010. The price for biogas from sewage treatment was 4.11 €/GJ (5.3 €c/km), and the price for received landfill gas was 4.95 €/GJ (6.4 €c/km) (Krupiński 2010).

In summary, the costs of biogas generation depend on the biogas plant capacity and on the substrate. Biogas generation from wastes and manure seem to be more economical than generation from grains. Based on the fitted trendline (Figure 5) the cost of biogas generation was estimated to be 21 €c/km when produced in a plant with the capacity of 1 000 Nm^3/h.

3.2 Upgrading

In order to use biogas as a vehicle fuel, its energy content must first be increased by removing the carbon dioxide. This process is called upgrading, where all the contaminants as well as the carbon dioxide are removed, and the content of the methane is increased from the usual 50–75 vol-% to more than 95 vol-%. Water and contaminants such as hydrogen sulphide and particulate matter must also be removed. The upgraded biogas is often referred to as biomethane. The energy content of one normal cubic metre (the volume of gas at 0°C and atmospheric pressure) of upgraded biogas is equivalent to that obtained from 1.1 litres of petrol, corresponding to 36 MJ. (Held 2008)

Various technologies can be applied for the removal of contaminants and for increasing the methane content of biogas. The removal of carbon dioxide is done in order to reach the required lower heating value of the gas. When removing carbon dioxide from biogas, small amounts of methane are also removed. The methane slope is usually between 0.5 and 2 % depending on the upgrading technique.

Upgrading methods applied in Europe at the end of 2008 are shown in Figure 6 (Kassel 2008).

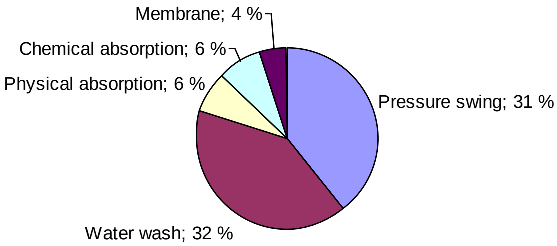

Figure 6. Upgrading methods applied in Europe 2008 (Kassel 2008).

3.2.1 Upgrading methods

The commonly applied commercial methods for upgrading biogas are described in the following sections.

3.2.1.1 Water scrubbing

Physical absorption is the most common technique for upgrading biogas. This method is based on the higher solubility of carbon dioxide than methane to water. In the water wash-scrubber column, carbon dioxide is dissolved in the water, and simultaneously the methane concentration in the gas phase increases. The gas leaving the scrubber therefore has an increased concentration of methane. The water leaving the absorption column is transferred to a flash tank where the dissolved gas, which contains some methane but mainly carbon dioxide, is released and transferred back to the raw gas inlet. If the water should be recycled it is transferred to a desorption column filled with plastic packing, where it meets a counter flow of air, into which carbon dioxide will be released. Micro-organisms may grow on the surface of the absorption tower, and thus the capacity may decrease and maintenance costs increase (Sweco 2005). (Petersson, Wellinger 2009)

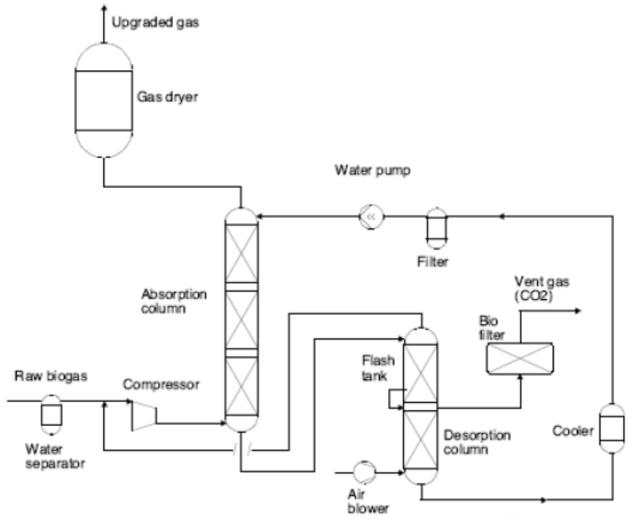

Figure 7. Water scrubbing system (Öhman 2009)

3.2.1.2 Pressure swing adsorption (PSA)

PSA separates different substances on the basis of their molecular size. The sorption media are molecular sieves, usually zeolite or activated carbon. The adsorption of CO_2 takes place at 4-7 bar, desorption at 0.05 bar. The received methane content is at least 96 vol-%. If hydrogen sulphide is present in the raw gas, it will be irreversibly adsorbed on the adsorbing material. In addition, water present in the raw gas can destroy the structure of the filter. Therefore the hydrogen sulphide and water need to be removed before the PSA-column. The advantages of the PSA method are that it needs no heat or chemicals. The disadvantages are methane loss, high electricity consumption, prior desulphurization and gas drying necessary. (Urban 2007)

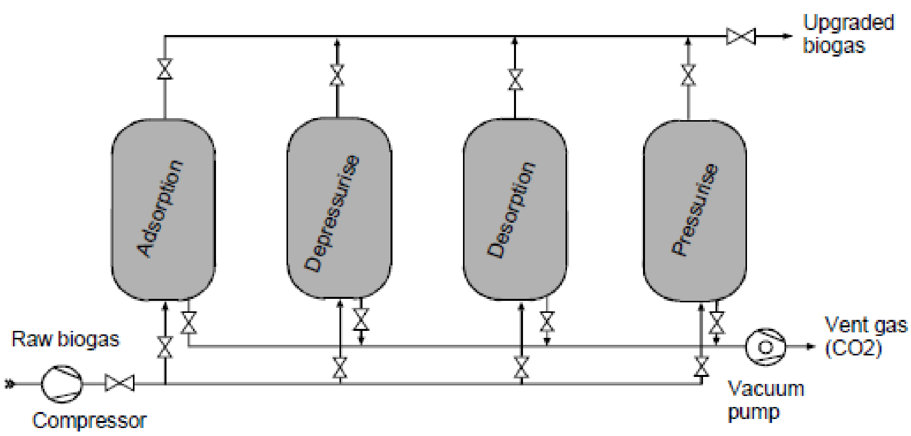

Figure 8. Pressure swing adsorption (PSA) system (http://methane-digester.net/tag/adsorber/).

3.2.1.3 Organic physical scrubbing

Organic physical scrubbing is very similar to water scrubbing, with the important difference that the carbon dioxide is absorbed in an organic solvent such as polyethylene glycol. Carbon dioxide is more soluble in polyethylene glycol than in water and for the same upgrading capacity the flow of the liquid phase can be lower, so the plant can be smaller. The polyethylene glycol solution is regenerated by heating and/or depressurizing. Hydrogen sulphide, halogenated hydrocarbons, water, oxygen and nitrogen may be removed together with carbon dioxide. However, a lot of energy is needed to regenerate the organic solvent from the hydrogen sulphide and therefore it is often removed prior to upgrading together with the other compounds mentioned. Selexol® and Genosorb® are examples of trade names for liquids used in organic physical scrubbing. (Petersson, Wellinger 2009)

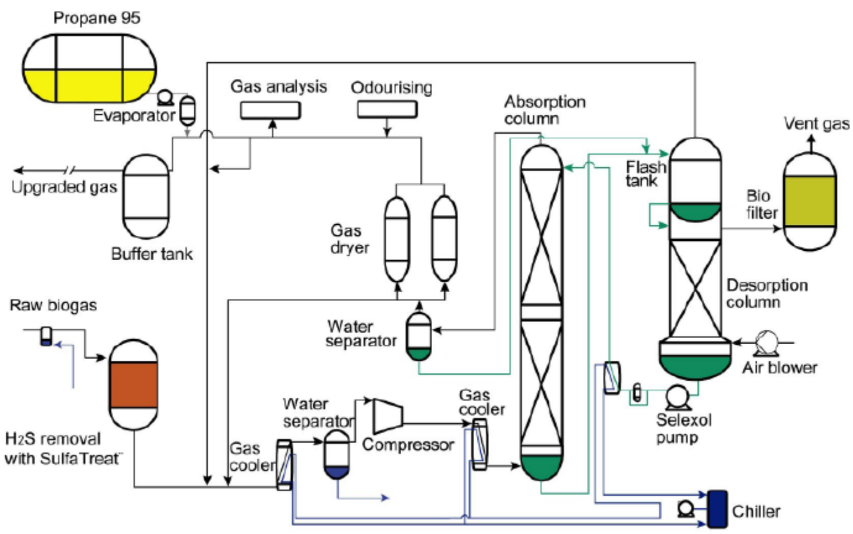

Figure 9. Organic physical scrubbing with Selexol® (Öhman 2009)

3.2.1.4 Chemical scrubbing

The principle of chemical scrubbing is similar to the other scrubbing methods described above. The solvents that can be used are alkanol amines like mono ethanol amine (MEA) or dimethyl ethanol amine (DMEA).The chemical is regenerated in a reverted chemical reaction usually driven by heat and/or a vacuum. In a typical MEA process, hydrogen sulphide is removed before the biogas enters the bottom of the absorption column. The gas meets a counter-flow of liquid and the carbon dioxide reacts with the chemical at low pressure. Since the reaction is selective, almost all the carbon dioxide and very little methane is removed. The chemical is regenerated through heating with steam which has the disadvantage of being energy consuming. (Persson et al. 2006)

3.2.1.5 Membrane process

Dry membranes for biogas upgrading are made of materials that are permeable to carbon dioxide, water and ammonia. Hydrogen sulphide and oxygen permeates through the membrane to some extent while nitrogen and methane only pass to a very low extent. Usually such membranes are in the form of hollow fibres bundled together. The process is often performed in two stages. Before the gas enters the hollow fibres it passes through a filter that retains water and oil droplets and aerosols, which would otherwise negatively affect the membrane performance. Additionally, hydrogen sulphide is usually removed with activated carbon before the membrane. The membrane either works at high pressure usually over 20 bar or at low pressures of 8–10 bar with lower methane losses. (Petersson, Wellinger 2009)

3.2.1.6 Cryogenic process

Carbon dioxide can also be separated from methane using cryogenic technology. This method is based on the fact that the two gases have different boiling points, which means that carbon dioxide can be removed by cooling the biogas to a liquid form. (Held 2008)

The cryogenic process is an emerging commercial technique, but it is not mentioned, e.g. in Figure 6 made in 2008. Commercial full-scale plants are under construction in some places in Europe.

Depending on the final temperature, the methane can be produced both in the gas or liquid phase (Persson *et al*. 2006). Figure 10 shows the principle of one commercial cryogenic process.

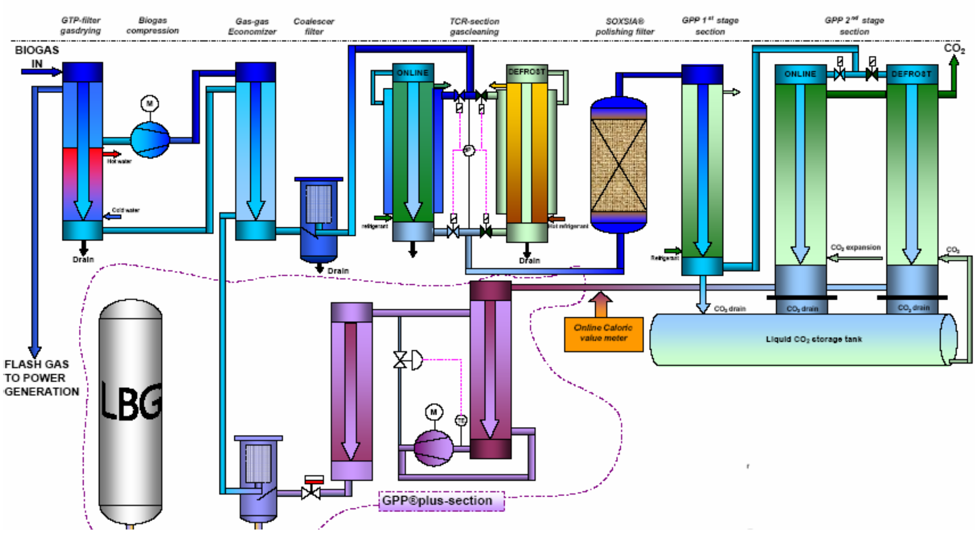

Figure 10. Cryogenic process with Scandinavian GtS (Scandinavian GtS 2010)

3.2.1.7 Emerging upgrading techniques

In situ methane enrichment

The *in situ* methane enrichment method is under development. Carbon dioxide is dissolved in the liquid phase of the digester tank. Sludge from the digester is circulated to a desorption column and then back to the digester. Process simulations showed a possibility to reach a biogas quality of 95 % methane with a methane loss of below 2 %. Cost estimations showed that for a raw gas flow below 100 Nm^3/h, the cost can be one third of the cost of conventional techniques. (Petersson, Wellinger 2009)

Ecological lung

The ecological lung method is also under development. In this process, carbon dioxide is separated from biogas using enzyme carboanhydrase. The production cost of the enzyme is still high, which affects the viability of the process, but biogas can be purified up to a methane content of 99%. (Petersson, Wellinger 2009)

3.2.2 Costs of upgrading

Investment

The total cost for cleaning and upgrading biogas consists of investment costs and operation and maintenance costs. In the case of investment costs, an important factor is the size of the plant. The total investment costs increase with increased plant capacity but the investment per unit of installed capacity is lower for larger plants compared to small ones. (Al Seadi *et al*. 2008)

Urban *et al*. (2009) estimated the costs of water and chemical scrubbing processes and pressure-swing processes. The capacities studied were from 250 to 2 000 Nm^3/h of raw gas. The electricity cost of 15 €c/kWh was used. The costs were estimated using a methane content of 97 % in upgraded biogas (biomethane).

Öhman (Petersson 2009, p. 45) studied the costs of commercial cryotechniques. The study includes three global manufacturers: Scandinavian GtS, Acrion Technologies and Prometheus Energy. The cost results for a raw gas capacity of 1 000 Nm^3/h were between 0.14 and 0.23 €c/Nm^3 (14–22 €c/km) of raw gas.

Pulsa (2008) studied the costs of three different upgrading methods for collected landfill gas with a raw gas capacity of 350 Nm^3/h and 1 400 Nm^3/h. The methods were 1) water scrubber with freezing dryer, 2) PSA with drying, sulphur and halogenated removal, and 3) cryogenic liquefaction with trace compounds removal. Also trace compound removal without upgrading was studied. In cases 1 and 2, the operating time was assumed to be 8 300 hours and the electricity intake 0.33 kWh/Nm^3 raw gas. In case 3, the yearly operating time was assumed to be 8 300 hours and the electricity intake 0.23 kWh/Nm^3.

Björkman has presented the investment costs of an amine-wash upgrading plant with a raw gas capacity of 750 Nm^3/h in Bekkelaget waste water treatment plant in Norway (Björkman 2010). The total investment cost of the upgrading plant including feasibility study, permits, tender documents and design, custom built upgrading plant with redundancy on rotating equipment, high pressure (200 bar) compressors and capacity for gas containers (7 containers) was 4 M€. The cost of the bare upgrading plant was 2 M€. Annual operating costs of the upgrading are estimated to be 226 k€, with prices of electricity 9.375 €c/kWh and heat 3.75 €c/kWh. (Björkman, email 2010)

According to Lappalainen (2010), the investment cost of a water scrubber Greenlane CSFR1200 with maximum raw gas capacity of 1 200 Nm^3/h was 1.9 M€.

Based on the figures given above, as well as Urban (2009) and Öhman (Petersson 2009, p. 45), the investment costs of biogas upgrading with different methods by raw gas capacity are shown in Figure 11. The details are also given in Appendix 1.

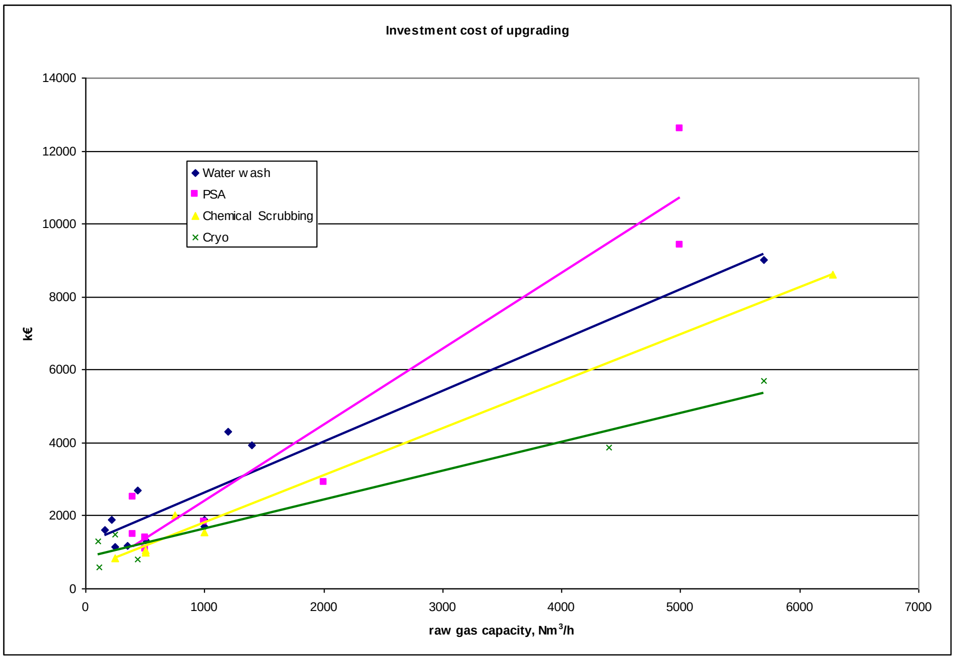

Figure 11. Investment costs of biogas upgrading techniques versus raw gas capacity.

Annual costs

The annual costs of upgrading plants are mostly composed of maintenance costs and usage costs like electricity consumption, water need, chemicals and operation. The process intakes are dependent on the upgrading process; for example, water scrubbers need more water than the cryogenic process.

The annual capital costs were calculated with 6 % annuity and a payback time of 15 years. Annual operating time was assumed to be 8 300 hours, which equals a utility rate of 95 %. Detailed calculations based on the figures given above are given in Appendix 1, Table 2.

An example of the annual costs of a water scrubber was estimated for Greenlane CSFR1200 using prices for electricity of 0.06 €/kW/h, water 1 €/m^3, oil 3 €/l. Energy consumption was estimated to be 204.6 kW. With an operating time of 8 300 hours per year, the total operating cost was 115.4 k€, including electricity cost of 101.9 k€/a, water cost of 830 €/a and lubricant oil cost of 12.7 k€/a. (Lappalainen 2010)

Roth *et al.* (2009) presented the upgrading costs for a water scrubber. The specific costs decreased from 19 to 7 €c/Nm^3 (18–7 €c/km) of raw gas, respectively, with increasing raw gas capacity of 100 to 600 Nm^3/h. The specific upgrading cost in a plant with a raw gas capacity of between 600 to 2 000 Nm^3/h stabilized to a cost level of 5 €c/Nm^3 (5 €c/km) of raw gas.

Benjaminsson *et al.* (2009) calculated the upgrading and distribution costs for upgraded biogas with capacities of 120 and 1200 Nm^3/h. The cost of conventional upgrading was 15.2 and 5.9 €c/Nm^3 (corresponding to 9 and 4 €c/km), respectively. The cost of the biogas cleaning before liquefying was estimated to be 9.0 and 1.6 €c/Nm^3 (5 and 1 €c/km), respectively. The liquefying processes were 55.1 and 11.4 €c/Nm^3 (33 and 7 €c/km), respectively.

Based on the figures given above, the calculated annual costs of the upgrading methods versus raw gas capacity are shown in Figure 12. The capital costs are included in annual costs. A trendline is plotted in the figure using the costs of the water wash technique.

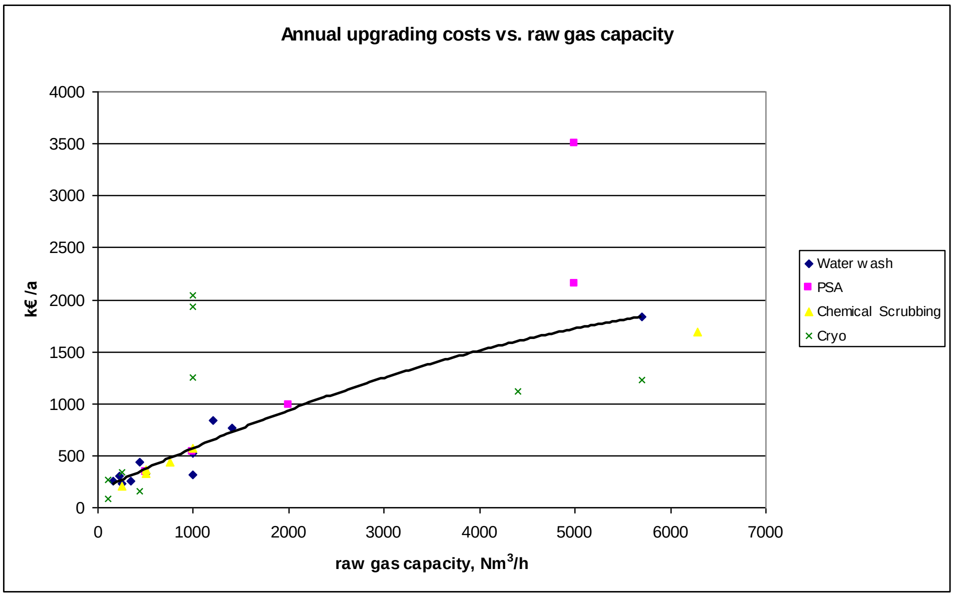

Figure 12 . Annual costs of upgrading.

Specific upgrading costs versus raw gas capacity are shown in Figure 13. The different upgrading methods were separated in the calculations. The results from the calculations made are shown in Figure 13, and the calculation details are given in Appendix 2. Also the specific cost results made by Roth *et al*. and by Benjaminsson *et al*. are shown in Figure 13 for comparison.

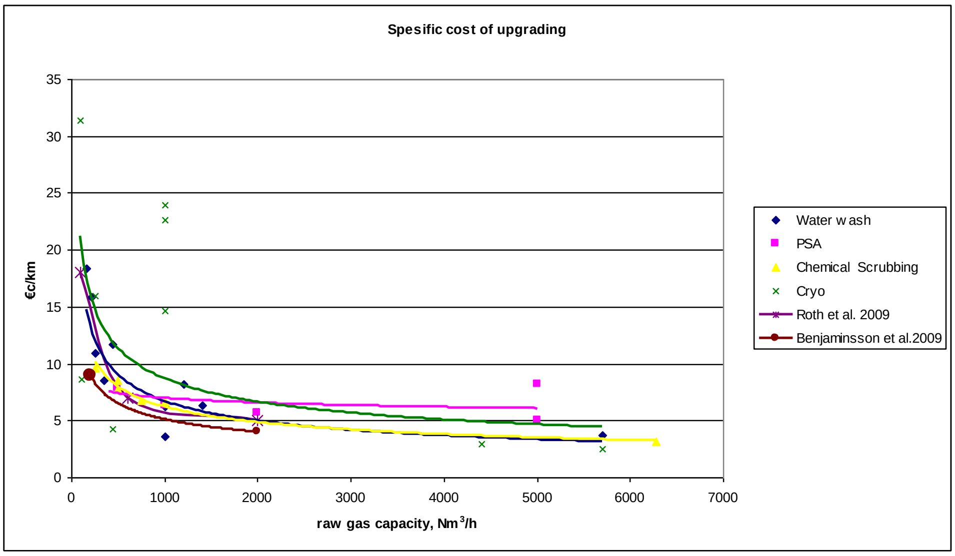

Figure 13. Specific upgrading costs vs. raw gas capacity, €c/km.

In summary, the upgrading costs depend on the upgrading process and on its scale. Water scrubbing had a quite similar cost to chemical scrubbing. Pressure Swing Absorption (PSA) had a similar cost to water and chemical scrubbing for plants with a raw gas capacity < 2 000 Nm^3/h. However, for larger flows, the cost of PSA can be almost double compared to other processes. As cryogenic upgrading is still quite rare, the cost estimations varied a lot between different data sources. Still, from Figure 13 it can be seen that the costs of a cryogenic process are the same or less than that of water and chemical scrubbing for raw gas flows > 1 000 Nm^3/h. The cost of upgrading for the further calculations was estimated to be 7 €c/km when upgrading 1 000 Nm^3/h raw gas using the trend line for water scrubbing in Figure 13.

3.3 Distribution

The distribution of biomethane from an upgrading plant to the filling stations can take place by pipeline or by vehicle. Distributed biomethane can be compressed or liquefied. This section on distribution is broken down into pipeline distribution and vehicle distribution.

The pressure, temperature, density and energy density data of compressed and liquid biomethane are shown in Table 5. As can be seen, 1 m^3 of liquid biomethane contains 2.6 times more energy than compressed biomethane to 200 bars.

Table 5. Main data of compressed and liquefied biomethane. (Benjaminsson 2009)

		Gas, NTP	Compressed gas	Liquid gas
	unit		CNG/CMG	LNG/LMG
pressure	bar	1	200	1
temperature	ºC	0	15	-162
density	kg/m^3	0.7	168	423
energy density	MWh/m^3	0.01	2.3	5.9

3.3.1 Pipeline distribution

Biomethane and liquefied methane can be distributed via local pipeline to filling stations or it can be injected into the main or regional natural gas grid. Local gas pipelines can be used to distribute biomethane to filling stations. Main natural gas grids are used to transport the natural gas to the regional grids for distribution.

Transported gas must be compressed to pipeline pressure, which is usually in local gas pipelines from 4 to 7 bar, in the regional natural gas grid 50–80 bar and in the main natural gas grid usually 200 bar. The pipeline pressure used varies in different countries and areas.

Before injection into the gas pipeline, the biomethane is odourized with a scented additive, usually tertiarybutylmercaptane (TBM), tetrahydrotiophene (THT) or ethyl mercaptane to enable the detection of any gas leaks. Injection into the natural gas grid may also need the addition of higher hydrocarbon (usually propane) to attain the same energy content as natural gas and thus to ensure a fair debiting of customers. Gas quality is measured to detect the need for additional propane. The gas quality is often measured with a gas chromatograph (Pulsa 2008).

The principles of injection in to gas pipelines are shown in Figure 14. The figure shows the main operations to local, regional and main gas pipelines.

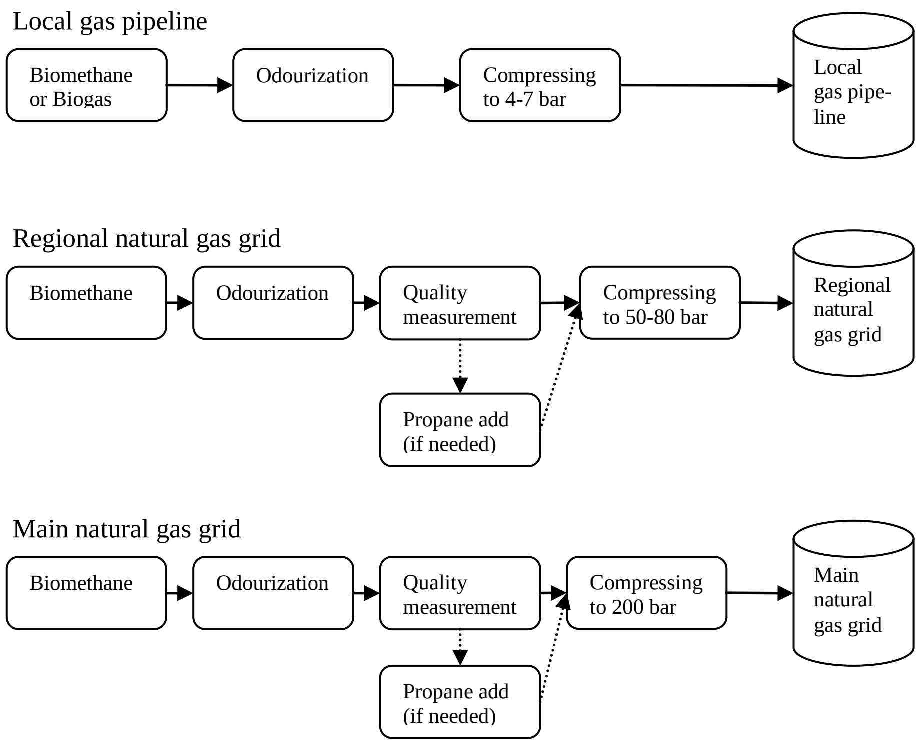

Figure 14. Principle picture of gas injection into local pipeline and natural gas grids.

Sweden, Switzerland, Germany and France have quality standards (certification systems) for biogas injected into the natural gas grid. The quality requirements are in most cases easily achievable with current upgrading processes. In Europe, biogas feed plants are in operation in Sweden, Germany, Austria, the Netherlands, Switzerland and France. (Al Seadi *et al*. 2008).

Liquefied biomethane can also be pumped via a local pipeline. The pipeline distribution of liquid methane is very similar to compressed gas distribution, only the feeding compressor must be changed for a cryogenic liquid pump, and the pipeline must be insulated to keep the temperature low to avoid evaporation of liquid methane. The inner diameter of the pipe is smaller than in a compressed gas pipeline.

3.3.1.1 Cost of distribution by pipeline

The pipeline investment cost depends on the environment, transported gas volume, pressure of the gas line and length.

The investment and annual usage and maintenance costs from different sources are listed to Table 6. The average building cost, including investment and works in a rural area was 94 €/m and in an urban area 270 €/m. However, the variation was large. On average, the annual usage cost was 8 % of the investment, and the annual maintenance cost was 1 % of the investment. The average total annual usage and maintenance costs were 9 % of the investment cost.

Table 6. Gas pipe line investment and annual usage and maintenance costs.

Gas pipeline		investment	usage	maintenance
source	area	€/m	€/m/a	€/m/a
Jarvis 2009	rural	50	4.02	0,1
Mårtenson 2007	rural	110	9.57	
Fallköping model_Biogasmax	rural	60		
Vainikka 2010	rural	100		
Urban et al. 2009	rural	150		
Gasum 2010	urban	290		
Jarvis 2009	urban	100	8	2,5
Mårtenson 2007	urban	430	37.41	

According to Mårtensson (2007), compressing the biomethane to a pressure of 4 bars costs 11 €c/Nm^3, equal to a specific cost of 7 €c/km.

The costs for building, usage, maintenance and compressing to 4 bar are calculated for urban and rural area using the figures listed above. The calculations are made for distances of 20, 100 and 200 kilometres. These calculations are shown in Appendix 2, Table 1. The specific costs in the rural area were respectively 11, 28 and 50 €c/km, and in the urban area 19, 69 and 132 €c/km.

Benjaminsson *et al.* (2009) estimated the distribution costs for two flow capacities. The processes were broken down into propane addition and compressing and the results are shown in Table 7. The values were also calculated as specific costs.

Table 7. Specific costs for propane addition and compressing (Benjaminsson 2009).

97% CH_4 capacity, Nm^3/h	120		1200	
	€c/Nm^3	€c/km*	€c/Nm^3	€c/km*
Propane addition	7.2	4.3	2.9	1.8
Compressing from 4 to 80 bar	5.8	3.5	2.1	1.3
Compressing to 200 bar	6.8	4.1	2.7	1.6

* Calculated

Pulsa (2008) presented the investment cost for propane addition including storage tank, vaporizer and installation. Propane tanks of volume 10 m^3 and 30 m^3 cost respectively 38 k€ and 45 k€.

Urban *et al.* (2009) estimated the investment costs of biomethane injection into the natural gas grid. The investment costs with three raw gas capacities are shown in Table 8. As can be seen, the specific cost does not vary between different capacities.

Table 8. Investment costs of injection plant (Urban et al. 2009).

	unit	Raw gas capacity		
	Nm^3/h	500	1 000	2 000
Biomethane	Nm^3/h	265	530	1 060
Pressure, max	bar	16	45	70
Distance	m	200	1 000	5 000
Injection station incl. Compressing (2-state), odorizing, quality and volume measuring (PGC), GDR-distance, propane addition	k€	480	820	1 410
Mechanic sealings	k€	8	25	75
NG net endings	k€	85	95	150
Piping (PE, PN10)	k€	26	150	750
Total investment costs	**k€**	**599**	**1 090**	**2 385**
Specific capital cost	€c/Nm^3	2.8	2.6	2.8
Specific cost *	€c/km	1.7	1.6	1.7

* calculated

Roth *et al.* (2009) calculated the distribution costs for gas pipeline and vehicle distribution of CMG and LMG. The studied capacities were 10 and 100 GWh/a. 10 GWh/a equals 1 MNm^3/a and 120 Nm^3/h of biomethane. 100 GWh/a equals 10 MNm^3/a and 1 200 Nm^3/h of biomethane. The currency value of the study was in SEK/kWh. 1 SEK/kWh was calculated to correspond to 95 €c/Nm^3 of biomethane. Figures 15 and 16 show the costs for distribution via gas pipeline (Gasnät), compressed biomethane (CBG) and liquid biomethane (LBG). The results showed that the gas pipeline distribution of 10 GWh/a was economical for a distance of less than 20 kilometres. For the capacity of 100 GWh/a the pipeline distribution was economically effective for up to 100 kilometres. For longer distances, LBG transportation was economically the most beneficial. A profitable pipeline for a biomethane capacity 5 MNm^3/a can be estimated to be between 20 and 100 km, probably near to 60 km.

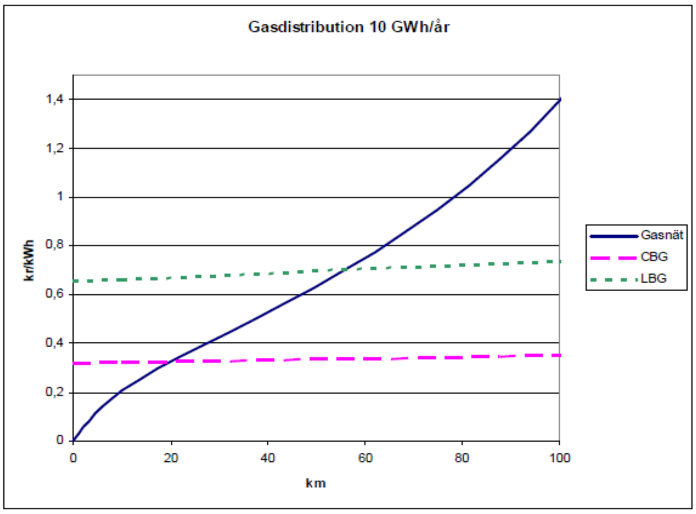

Figure 15. The costs of distribution types for biomethane capacity 10 GWh/a, equals 120 Nm^3/h and 1 MNm^3/a of biomethane (Roth *et al.* 2009).

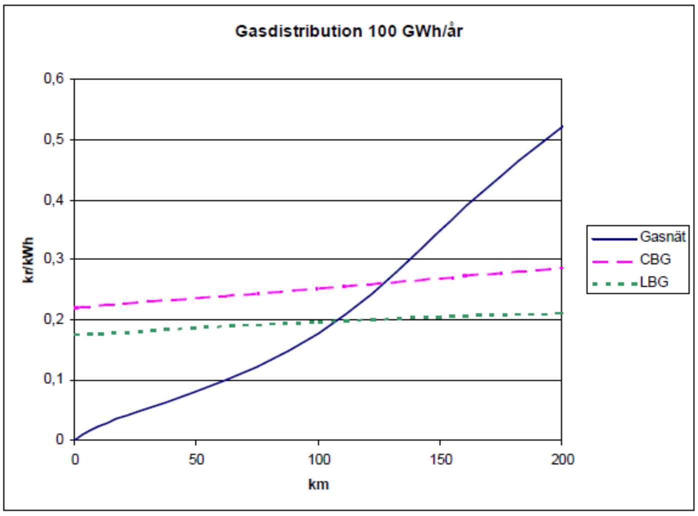

Figure 16. The costs of distribution types for biomethane capacity 100 GWh/a, equals 1 200 Nm^3/h and 10 MNm^3/a of biomethane (Roth *et al.* 2009).

Mårtensson (2007) calculated the profitability of a gas pipe construction versus vehicle distribution, as shown in Figure 17. The line represents the value where the cost for construction of a gas pipe equals the cost for distribution of the gas by vehicle. The biogas production per year was plotted on the y-axis and the distance from the production plant to the gas grid was on the x-axis. As can be seen from Figure 17, for a plant producing 5 MNm^3 yearly and located more than 15 km from the gas grid, transport by vehicle was more profitable than distribution by a gas line.

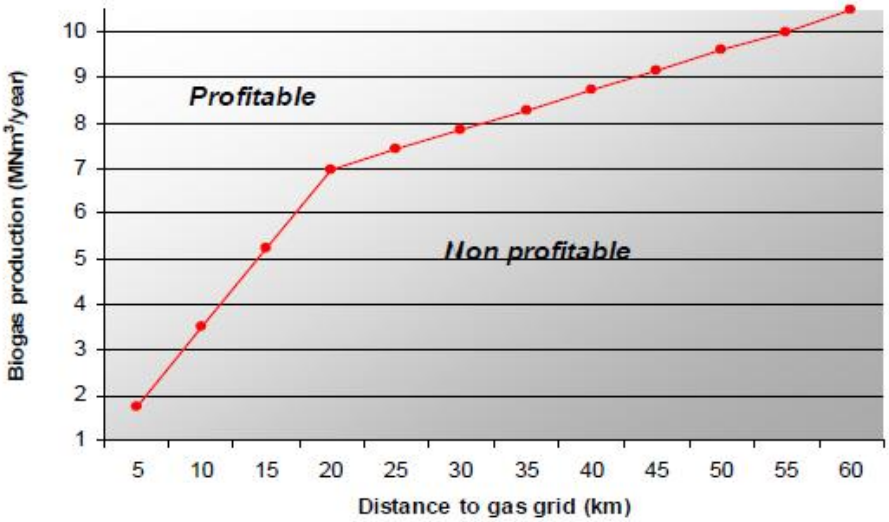

Figure 17. Profitability of gas grid construction versus vehicle distribution (Mårtensson 2007).

In summary, the pipeline investment cost depends on the building environment, transported gas volume, pressure of gas line and length. The urban area had almost three times higher investment costs than the rural area. There was a lack of data for usage and maintenance costs, but the combined usage and maintenance cost was estimated to be 9 % of the investment cost. The cost of injection into the natural gas grids has varying results. The calculations made by Urban et al. (2009) showed that the specific cost of the injection was < 2 €c/km and it was not dependent on the capacity of injected biomethane. On the other hand, Benjaminsson (2009) presented results where the specific costs were clearly dependent on the capacity.

3.3.2 Vehicle distribution

When pipeline distribution is not available, the biomethane can be distributed by vehicle as a compressed or liquefied biomethane.

3.3.2.1 Compressed gas

Compressed biomethane can be transported to the filling stations using either a gas trailer or hook-lift trailers. The pressure in a gas trailer is 200 bars and in a hook-lift trailer up to 300 bars.

A gas trailer (Figure 18) comprises many 90-litre pressure tanks, and the total geometric volume of the tanks can be up to 27 m^3. Thus, the transported gas volume can be up to 6 000 Nm^3 with a pressure of 200 bar. (Sweco 2005)

Figure 18. Gas trailer (Sweco 2005).

A hook-lift trailer (Figure 19) comprises 147 50-litre pressure tanks with the geometric volume of 7.35 m^3. The pressure is 200 bar, and the volume of the gas is about 1 900 Nm^3. A hook-lift trailer is transported with a truck that can deliver three hook-lift trailers at the same time. The maximum gas volume for a hook-lift trailer is therefore 5 700 Nm^3 within one transportation. (Sweco 2005)

Pressure tanks can be also made from composite material. Composite material weighs less, and thus the capacity of one hook-lift trailer can be increased to 4 850 Nm^3. A truck can deliver two of this kind of hook-lift trailers, and thus the total transported capacity can be 9 700 Nm^3. (Benjaminsson 2009)

When a hook-lift trailer tank is empty, it is replaced with a full one. Trucks are used to haul the trailers. Compared to the gas trailer, the hook lift system is relatively expensive since the amount of gas that can be distributed by truck is limited. (Svenssen *et al*. 2009)

Figure 19. Hook-lift trailer (Sweco 2005).

3.3.2.2 Liquefied Methane

Methane gas is liquefied by cooling to -162 ºC. As a cryogenic liquid, it takes up about 1/600 of the volume of uncompressed gas, making it an easier product to store and to transport. Typically one 45 m^3 tank is equal to 26 250 Nm^3 of methane gas. Transportation takes place with cryogenic tanks (Figure 20) having the same construction as for other cryogenic liquids, e.g. nitrogen and helium. (Hansson 2008)

In Sweden, Cryo AB offers a 21-tonne capacity tanker, with a boil-off[12] of 0.9 % per day, giving it a "hold time" of about 10 days. Swedish gas delivery company Gasnor uses LNG lorries delivered by Ros Roca in Spain. These load 20–23 tonnes per trailer. LNG lorries take 1–2 hours to load and to unload. (Hansson 2008)

Figure 20. LNG lorry (www.prometheus-energy.com).

3.3.2.3 Cost of distribution by vehicle

According to Sweco (2005) in Sweden, the investment cost of one gas trailer was 150 000 € and the transportation cost was 45 €/h. The investment cost of a hook-lift trailer was 50 000 € per hook lift trailer and transportation was 80 €/h.

According to Mårtensson (2007), the distribution of compressed biomethane by vehicle had the cost of 10 €c/Nm^3, equal to 7 €c/km.

Benjaminsson *et al.* (2009) studied the distribution costs for biomethane capacities of 120 and 1 200 Nm^3/h. The cost for CMG distribution by hook-lift trailer was respectively 5.2 and 2.2 €c/Nm^3, which equals 3.1 and 1.3 €c/km. The cost for LMG distribution by LMG trailer was respectively 3.4 and 0.4 €c/Nm^3, equal to 2.1 and 0.2 €c/km.

According to Hansson (2008,) the investment cost of a cryogenic tank of 21 tonnes with a geometric volume of 45 m^3, normalized volume of 26 250 Nm^3, was 270 000 €. Loading and unloading of the tank took 4 hours and presented a working cost was 55 €/h. The transport rate was 1.5 €/km.

The costs of CMG and LMG distribution by different types of vehicles were calculated using the references listed above. The calculated specific costs of different distribution types versus distance are shown in Figure 21. The calculations were made for a biomethane capacity of

[12] Cryogenic tanks have two layer tanks with vacuum in the intermediate space to reduce heat transfer. As more and more LNG is gasified into this layer however, the rate of heat transfer is increased. It is required to pump this gas somewhere and it can be performed by the refuelling system. (Hansson 2008)

620 Nm^3/h, which equals 5 MNm^3/a. The pipeline cost was calculated using previously presented average costs including compressing to 4 bar. Calculations were made for distribution distances of 20, 100 and 200 kilometres. These calculations are shown in Appendix 2, Table 2. The specific costs of CMG distribution distance of 20 km varied from 3 to 6 €c/km, in which case a gas trailer had the lowest costs. Respectively, the distribution of LMG for 20 km had an average specific cost of below 1.4 €c/km. Thus, biomethane was more profitable to distribute 20 km or more using vehicles instead of a pipeline.

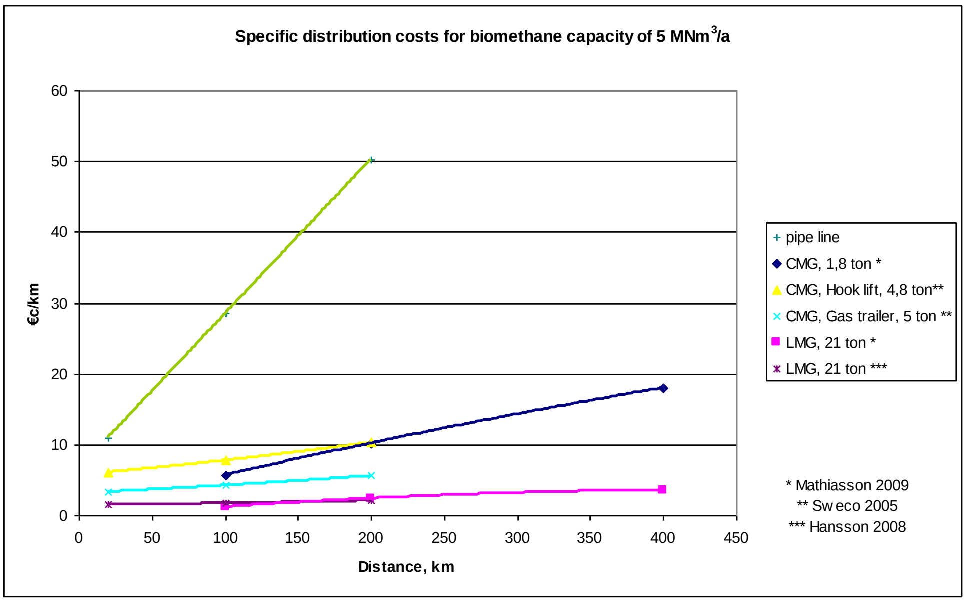

Figure 21. Specific costs of distribution vs. distance, €c/km.

In summary, for the biomethane capacity of 5 MNm^3/a the profitable distribution type was by vehicle, especially with LMG lorry distances over 20 km.

3.4 Filling stations

Filling stations include storage tanks, compressors and refuelling systems. The storage capacity depends on the number of buses and refuelling places (nozzles). Storage capacity is often planned for one day's capacity. Storage tank pressure is at least 200 bar.

3.4.1 Slow filling station

In slow filling stations, the refuelling time is typically five to seven hours. This system does not have back-up storage tanks and the gas is compressed into the vehicle tank at the same time the gas is transported to the filling station or compressed from gas tanks. The buses in bus depots are usually filled using a slow filling system which has many slow filling nozzles and a few fast filling nozzles.

Figure 22 shows an example of the principle of a slow filling station in Lille, France. The gas supply can be replaced with gas trailers. Buffer storages are needed for a fast filling opportunity.

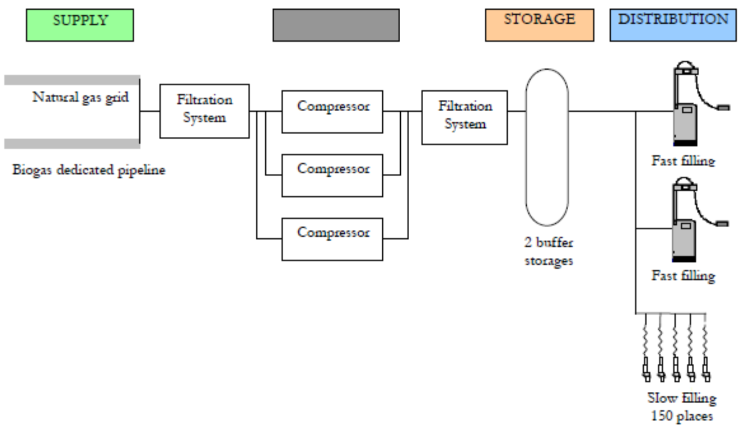

Figure 22. Principle of slow filling station (Ferré *et al*. 2009)

Slow filling stations can also be LCMG (Liquefied to Compressed Methane) stations, where the liquid methane is stored and then on demand either gasified to CMG (Compressed Methane Gas) or simply pumped over to an LMG driven vehicle or an LMG carrier. Restoring LMG back to gas involves adding energy to the product by evaporation and increasing of the gas temperature. This is performed by heat exchange with a heating agent, usually air. Vaporization is least effective in a humid climate at around 0°C, when a maximum of ice build-up on the evaporator appears. Lower temperatures mean that the air contains less heat, but it also contains less water and thus the level of ice fouling is lower. Air evaporators are often built in pairs so that one of the two can be de-iced while the other is running. The maximum capacity of air evaporators is typically 3 700–3 900 Nm^3/hour, while it can be as low 1700 Nm^3/hour when covered in ice. (Hansson 2008)

3.4.2 Slow filling station costs

The slow filling station costs were dependent on the maximum flow capacity, yearly capacity and number of dispensing nozzles.

Ferré *et al*. (2009) found that a bus depot with 150 slow filling dispensers and two fast filling dispensers had an investment cost of 1.8 M€. The cost included engineering 33.5 k€, construction 156 k€, three high pressure compressors 250 bar 990 k€, distribution items and compressor 600 k€ and connection to the gas grid 11.6 k€. Usage costs were 32.5 k€/a and planned maintenance costs were 90 k€/a. Bus depot filling station for 50 to 100 buses was calculated to cost 650–1 000 k€.

According to Vainikka (2010), the costs of filling stations vary depending on the type of station, external factors (e.g. intake pressure, electricity, site cost) and customer requirements. Based on experiences, the total operation and maintenance costs may vary from 8 to 75 €c/Nm^3 (5 to 45 €c/km). In the example from Finland, the investment cost of a bus depot for 50 buses was 1.2 M€ and usage costs were 10 €c/Nm^3 (6 €c/km). Refilling capacity of the depot was 2.5 MNm^3/a (equals 6 850 Nm^3/d), maximum capacity of 800 Nm^3/h and the refilling process was conducted at night.

Sweco (2005) has given the following cost estimations for a bus depot for 35 buses in Lidingö in Sweden. The refilling capacity of the depot was 1.3 MNm^3/a (equals 3 600 Nm^3/d) and maximum flow capacity 600 Nm^3/h. The investment cost of the filling station was 2 M€ and estimations for the annual cost were 285 k€. The investment and annual costs are broken down into detail, and shown in Table 9. From the annual costs the capital cost comprises 72 %, usage 22 % and maintenance 6 %.

According to Ekelund (2008), the annual costs of a slow filling station in Sweden consists of capital cost 48 %, electricity 25 % and maintenance 27 %. The capital cost calculations were made using a rate of 4 % and a 16-year payback time.

Table 9. Investment and annual cost profiles of bus depot filling station (Sweco 2005).

	k€	%
Investment costs		
Gas compressors, 2 x 310 k€	620	31 %
Electronic	20	1 %
Gas storage	250	13 %
Land and building	430	22 %
Installation	160	8 %
Dispenser	60	3 %
Planning, permits etc.	160	8 %
Unexpected costs	300	15 %
Total investment cost	2 000	100 %
Annual costs		
Capital cost	206	72 %
Daily control etc.	12.5	4 %
External service	5.2	2 %
Electricity	45.5	16 %
Spare parts	5	2 %
Maintenance	11	4 %
Total annual cost	285.2	100 %

Ferré *et al.* (2009) presented filling station techniques and investment costs for refilling waste-collection trucks and buses. The data obtained is shown in Table 10.

Table 10. Slow filling station costs and techniques (Ferré *et al.* 2009).

	Vehicles	Wastes collecting trucks		Buses
	pieces	12 to 25	40 to 100	50 to 100
Compressors	pieces	2	3	3
	Nm^3/h	450	450	450
Dispenser	pieces	2	2 in parallel	1 per bus
Surface	m^2	1000 -1200	1200 - 1500	depot + 250
Process station	k€	400	600	650 - 1000
Civil engineering	k€	100 - 200	200 - 300	

A back-up system with an LNG lorry costs 460 k€. This estimation included an LNG lorry (310 k€), piping (40 k€), planning and permits (30 k€), ground works (20 k€) and reserve for unexpected costs 60 k€. (Sweco 2005)

The costs of slow filling stations were calculated using the above given figures. Details of the calculations are shown in Appendix 3. As presented earlier in this assessment, the costs for different stages from biogas to vehicle fuel were estimated for a capacity of 1 000 Nm^3/h raw gas, which equals 620 Nm^3/h (14 400 Nm^3/d and 5 MNm^3/a) biomethane. According to the calculations, one slow filling station serving about 50 buses needs about 7 000 Nm^3/day biomethane (230 km/d/bus · 0,6 Nm^3/km · 50 buses). Thus the generated biomethane of 620 Nm^3/h was calculated to serve two bus depots with about 50 buses.

In summary, the average investment cost for a slow filling station for 50 buses was ca 1200 k€. The specific cost for such a filling station was 9 €c/km. respectively. Because the generated biomethane of 620 Nm^3/h can serve two such bus depots, the cost of refilling can be estimated to be 18 €c/km for further calculations.

3.4.3 Fast filling station

In fast filling stations the maximum refuelling time is 7 minutes per bus. With a storage tank pressure over 200 bars, the gas flows straight into the vehicle tank, and with a pressure below 200 bars, the gas is compressed up to 200 bars in the vehicle tank.

The principle of a fast filling station is shown in Figure 23. The gas supply can be replaced with a gas trailer or pipeline.

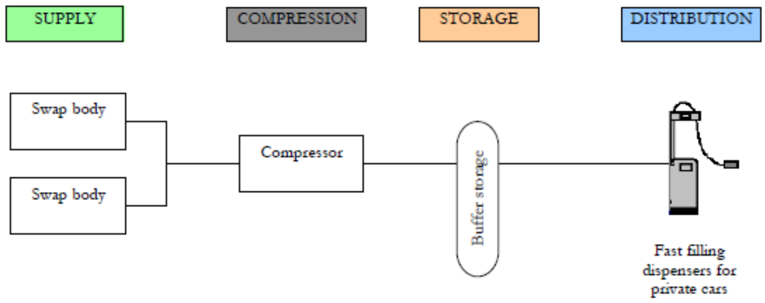

Figure 23. Principle of fast filling station (Ferré *et al.* 2009)

3.4.4 Costs of fast filling stations

According to Vainikka (2010), in Finland a small public fast filling station investment cost is about 600 k€ and usage costs of 20 €c/Nm^3. The capacity of the fast filling station was 200 Nm^3/h with 4 bar intake pressure. (Vainikka 2010)

In Sweden a small fast filling station investment cost was studied to be about 385 k€ including compression station, storage 2 000–3 500 Nm^3, two dispensers and installation. The installation cost was estimated to be about 55 k€. (Ferré *et al.* 2009)

According to Lappalainen (2010), the investment cost of a fast filling station with a capacity of 550 Nm^3/h using two compressors was 500 k€, and with three compressors 750 k€. The investment cost includes storage tank, compressors, filling station and a payment terminal. Installation work was not included in the costs.

Svensson (2010) reported the costs for one Italian multi-dispenser fast filling station selling petrol, diesel, hydro-methane and biomethane. The Total investment cost of the service station was 4.5 M€. Biomethane consumption was about 18 000 Nm^3/year, equivalent to a biomethane capacity of 50 Nm^3/h. (Svensson 2010)

Benjaminsson et al. (2009) estimated the costs of an LMG backup storage for biomethane capacities of 120 and 1 200 Nm^3/h. The costs were 4.5 and 0.7 €c/Nm^3 (2.7 and 0.4 €c/km) respectively.

Roth et al. (2009) presented the costs of public filling stations for a capacity of 5 GWh/a, which is equal to 63 Nm^3/h biomethane. The cost for gas refilling integrated to an existing filling station was 0.2 SEK/kWh (19 €c/Nm^3 biomethane, 11 €c/km). The cost for a new filling station was 0.28 SEK/kWh (27 €c/Nm^3 biomethane, 16 €c/km).

According to Ferré *et al.* (2009), the annual costs for a filling station can be broken down as follows: gas 50%, maintenance 27%, investment 18% and electricity 5%.

Ferré *et al.* (2009) reported the costs of the filling stations in Göteborg, Sweden, as shown in Table 11. L-station means a public station connected to the gas grid, and E-station means a public station where gas is supplied by containers or trailers. The example of a public fast filling station with an investment cost of 484 k€ is detailed in Figure 24.

Table 11. Filling station costs in Göteborg, Sweden (Ferré et al. 2009).

	L-station	E-station	Bus filling station
Investment	375 500 €	236 200 € (compressor + dispenser with 2 filling nozzles, civil engineering excluded) 85 000 to 108 000 € per container	Depends on the number of buses From 859 200 to 2 685 000 €
Gas supply	Pipeline of the distribution grid (4 bar) or pipeline of the transmission grid (28 bar)	Trailer or containers of 19 tonnes max. (i.e. ~ 2,550 - 3,700 Nm³) at 200 bar with 90 L compressed gas bottles	Pipeline or Pipeline and container trailer
Compression	1 or 2 hydraulic compressor(s)	1 hydraulic compressor	3 hydraulic compressors
Storage	< 4 000 L of water at at 250 bar max	< 4 000 L of water at 200 bar	Storage not necessary, only a buffer
Refuelling	Booster compressor (1st compressor is re-used) Distribution at 230 bar max. (200 bar at 15°C)	Booster compressor (1st compressor is re-used) Distribution at 230 bar max. (200 bar at 15°C)	Fast filling (possible storage) or Slow filling

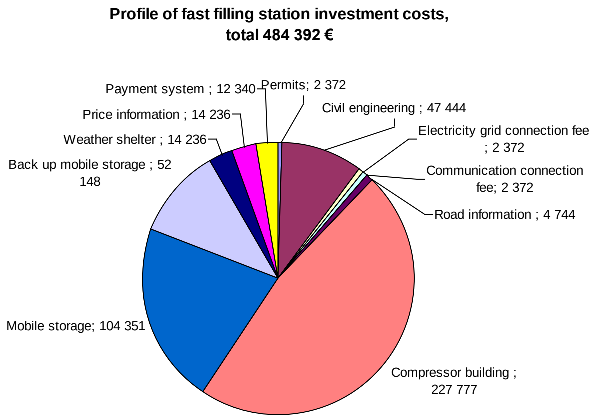

Figure 24. Investment cost profile of public fast filling station (Ferré *et al*. 2009).

Based on the figures given above, the costs of filling stations were calculated and given in Appendix 3, Table 1. As presented earlier, the costs for different stages from biogas to vehicle fuel were estimated for a capacity of 1 000 Nm^3/h raw gas, which equals 600 Nm^3/h (14 400 Nm^3/d and 5 MNm^3/a) biomethane. According to the calculation that one fast filling station needs about 3500 Nm^3/day biomethane, the 600

Nm^3/h generated biomethane can be calculated to serve four fast filling stations.

Benjaminsson and Nilsson (2009) reported the costs for a public filling station with a capacity of 5 GWh/a, which equals 0.5 MNm^3/a and 63 Nm^3/h of biomethane. The specific costs for a filling station connected to a pipeline were 0.18 SEK/kWh (10 €c/km), using compressed biomethane 0.14 SEK/kWh (8 €c/km) and using liquid biomethane 0.16 SEK/kWh (9 €c/km).

In summary, the investment cost of a fast filling station depends on maximum flow capacity, daily capacity, building land and gas supply method (pipe or vehicle). The investment cost varies from 140 to 900 k€, averaging about 500 k€. The specific cost varies between 8 and 34 €c/km, averaging about 20 €c/km.

3.5 Commuter buses

The bus types used in local traffic are commonly single-decker buses, or double-decker buses and articulated buses.

3.5.1 Technical data of buses

The technical design of biomethane-driven vehicles is exactly the same as for vehicles fuelled with natural gas. Heavy vehicles such as buses are constructed to use gas alone. There are two main engine types: spark-ignition engines and stoichiometric engines. Under development are also manifold injection engines with diesel-like engine efficiency. Spark-ignition engines have 25–30 % higher fuel consumption than diesel engines because of lower engine efficiency. Stoichiometric gas engines have the same fuel consumption as spark-ignition gas engines (Hartikka 2010). (Nylund 2010)

Fuel tank volumes of a gas buses are typically from 1 000 to 1 700 litres. With a filling pressure of 200 bar the energy content is equal to 200–340 litres of diesel. It is forbidden to drive when the gas tanks are totally empty, and thus 10 % of the volume cannot be used. This means that the operational range of the gas bus is maximum 400 to 450 km. (Nylund et al. 2009)

Emissions of nitrogen oxides, carbon monoxide, hydrocarbons and particles are regulated by the European Union. The main emission compounds that must be controlled are particles and nitrogen oxides. Gas engines have very low particulate emissions and therefore there is no need for particle reduction. Nitrogen oxides can be reduced either during combustion with an exhaust gas recirculation (EGR) system or by after-treatment devices like selective catalytic reduction (SCR). Gas engines can also use a combination of stoichiometric combustion and three-way catalyst (TWC). Optimized engines with after-treatment devices produce very low regulated and unregulated emissions. (Nylund, Aakko-Saksa, Sipilä 2008)

Particle emissions from diesel engines can be reduced using, e.g. diesel particle filters (DPF), particle oxidation catalyst (POC) or continuously regenerating trap (CRT). DPFs have an effective life of 7 ½ years (Lowell *et al*. 2005). POC can achieve a particle conversion of 30–70 %. CRT can be combined with SCR, called SCRT. Diesel fuel powered buses need SCR to pass EURO V requirements. It is also estimated that diesel fuel buses need EGR, SCR and DPF to pass EURO VI requirements. (Nylund, Erkkilä, Hartikka 2007) (Murtonen, Aakko-Saksa 2009)

Most of the European heavy-duty manufacturers have chosen SCR technology for Euro IV and Euro V and the voluntary EEV certification class. For Europe, SCR currently delivers better fuel efficiency than EGR. For the upcoming Euro VI regulation, roughly equivalent to U.S. 2010 and scheduled for 2013–2014, the Commission has predicted that fuel consumption will increase by 2–3%. (Nylund, Aakko-Saksa, Sipilä 2008)

3.5.2 Costs of commuter buses

Investment and annual costs depend on the manufacturer, bus type (e.g. length, low floor body), engine power and the fuel used. Cost data collected from the bus operators were varying and comparison of gas buses with diesel buses was not representative in all cases because not all the bus operators had similar gas and diesel buses. Cost estimates were also collected from the manufacturers.

The cost estimations for Volvo 7700 gas and diesel buses with a lean-burn 9.36 litre engine, 2-axis, low-floor body and length of 12 meters is presented in Table 12. Both buses have the same engines including EGR and SCR systems for nitrogen oxides. The engines meet the EURO V emission standards. The investment costs did not include Value Added Tax (VAT). Annual usage and maintenance cost estimations were averaged for 5 years assuming a yearly mileage of 75 000 km. The investment and operation costs for the gas bus were 25 % more compared to the diesel bus. (Eskelinen 2010)

Table 12. The investment and annual costs of Volvo 7700 CNG and Diesel buses (Eskelinen 2010).

	Investment	Usage and maintenance
	k€	€c/km
Diesel	230	18
CMG	288	22.5

According to Haapakoski (2010), the investment costs for an after-treatment device DPF is about 6 500 € and for SCR+DPF combination about 14 500 €. The estimations were made for an engine volume of about 10 litres.

According to Shevchuk (2010), the investment cost of a 2-axis Solaris Urbino 12 Low entry was SEK 2.5 M, equivalent to 250 k€. The engine type was stoichiometric with an after-treatment three-way catalyst (TWC) device. The maintenance costs excluding fuel costs are estimated to be on average 0.247 €/km over 10 years using a yearly mileage of 100 000 km in the calculations.

Lowell et al. (2005) in New York, USA, studied the costs of diesel and CNG buses between 2000 and 2004. The study included the costs of aftertreatments giving the investment cost for DPF of USD 5 900, the annual costs for filter replacements/reconditioning of USD 137 and filter cleaning of USD 670. The annual cost of DPF was thus estimated to be 14 % of the investment cost.

Nylund, Erkkilä and Hartikka (2007) studied the urea solution consumption of SCR after-treatment devices. The results showed the consumption to vary between 1 and 2.5 litres per 100 km. The price of urea solution was given as 0.55 €/litre.

Posada (2009) listed various cost comparisons between CNG and diesel buses. The first listing was from the American Public Transportation Association's Transit Vehicle Database between 2005 and 2007. The average for CNG buses was USD 376 000 and for diesel buses USD 329 500, thus over thee three years CNG buses cost 14% more than diesel buses. The assessment mentioned also that in Europe, according to the International Association of Public Transport (UITP), in 2006 a CNG/powered 12-meter transit bus was about 15–20% more expensive than a diesel/powered bus.

Clark *et al.* (2009) studied the costs of diesel and CNG buses in the USA. The investment costs in 2007 for a 40-foot (12 meters) diesel bus was on average USD 310 000 and for a CNG bus USD 340 000. Thus the CNG bus costs 10 % more. The maintenance costs are estimated respectively to be USD 0.59 and USD 0.68 per mile, thus the maintenance cost of CNG buses is 15 % higher than in diesel buses.

According to Petrović *et al.* (2009) the investment costs of diesel and CNG-powered buses in Belgrade, Serbia, were 80 and 100 k€ respectively from the Serbian manufacturer Ikarbus.

According to Andersson (2010), in Finland the maintenance costs of gas buses is 1.5 times more compared to diesel buses. This data was based on the manufacturer information because the bus operator did not have similar diesel buses in operation.

Ekelund (2008) reported a 23 % increased investment cost for gas buses compared to similar diesel buses. Increased gas fuel cost in city traffic was reported to be 14 % compared to diesel buses. The service costs for gas buses were 2.4 times more than for diesel buses. The study also mentions an increased cost of about 0.2 €c/km from picking up gas buses when operation is interrupted caused by fuel based reasons.

The calculations for bus usages are shown in Appendix 3, Table 2. The calculations were made using the investment and estimated annual costs for a diesel bus with SCR and a bus with SCR and DPF. Gas buses with spark-injection and stoichiometric engines are also presented. Bus types, lengths and masses were quite comparable. The calculations are based on the figures given above, with a yearly mileage of 60 000 km, 6 % rate and payback time of 15 years. When an assumed diesel fuel consumption increase of 2 % for the EURO VI regulation was taken into account, the diesel consumption rose to 0.46 l/km for a diesel bus using DPF. The yearly cleaning and maintenance costs of DPF were estimated to be 0.91 k€ (14% of 6.5 k€) per bus according to Lowell *et al.* (2005). The urea consumptions used for all SCR buses was 2 litres per 100 km at a price of 0.55 €/l according to Nylund, Erkkilä and Hartikka (2007). The results of the calculation showed that a particle emission reduction with DPF in diesel buses increased the specific cost per mileage by 4 % (from 59 to 61 €c/km). The compared gas buses were quite similar to each other. On average the investment costs of gas buses were 17 % more than the investment costs of diesel buses. The annual costs of the gas buses were 19 % more than annual costs of diesel buses. The usage and maintenance costs in gas buses were on average 31 % higher than in diesel buses.

In summary, the total costs of bus usage depend on bus body type, engine volume and type, driven distances and cycles, etc. The investment cost of a EURO V certified gas bus was 17 % higher than that of a corresponding diesel bus. The annual costs of gas buses were 14 % more than the annual costs of diesel buses. Maintenance and usage costs were calculated to be 31 % higher in gas buses than in diesel buses. The calculated costs of diesel buses with EURO VI certification (proposed to be required from 2014 onwards) increased the total costs by 4 % on the EURO V version. In further calculations, *the total specific cost of a diesel bus was 59 €c/km and a gas bus on average 70 €c/km.*

3.6 Total costs

The costs of biogas generation with a capacity of 1 000 Nm^3/h, upgrading, distribution and refilling versus vehicle mileage are shown in Figure 25. Also the cost of diesel usage and cumulative costs of biomethane use are presented. The calculations were made with a diesel price of 1.0 €/litre. The fuel consumption of a gas bus was assumed as 0.6 Nm^3/km and a diesel bus 0.45 litres/km. The distribution by pipeline was estimated for a distance of 20 km in a rural area, and CMG distribution using gas trailer. The cost of the refilling station was estimated for a bus depot with 50 dispensers and did not include the gas price cost.

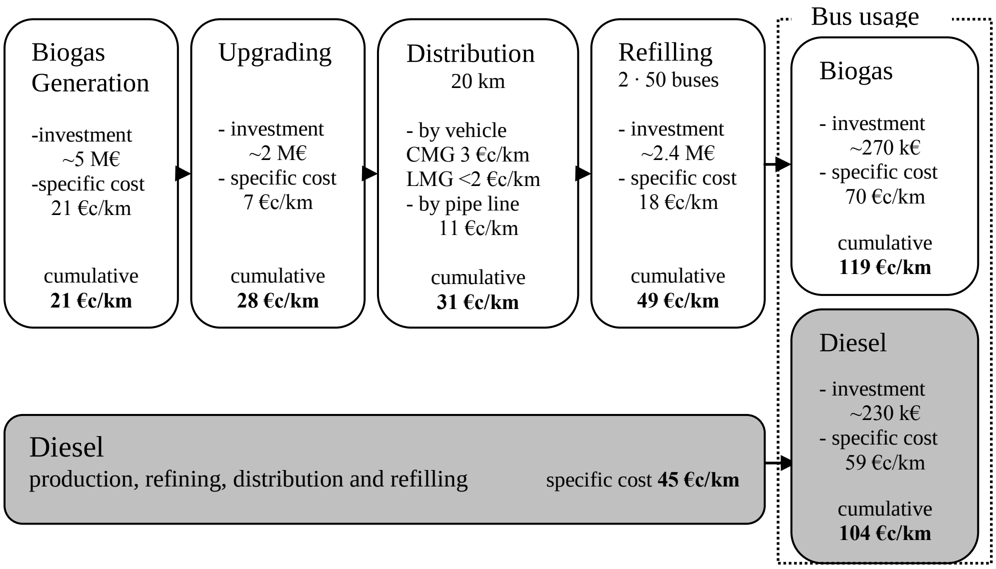

Figure 25. The specific costs of the different stages for a biogas generation capacity of 1 000 Nm^3/h.

As can be seen from Figure 25, the total specific cost for biogas generation of 1 000 Nm^3/h, upgrading, distributing CMG by vehicle and refilling was 49 €c/km. Respectively, the specific cost for diesel was 45 €c/km. For natural gas the specific cost was 48 €c/km, being at the same level as the biomethane production cost. Biomethane as a fuel was 9 % more expensive than diesel fuel. The diesel and natural gas prices included the coverage, but the biomethane cost calculations did not include it. Thus, an increased sales price for biomethane can be assumed compared to the cost calculations.

The total specific cost for biomethane generation, upgrading, distribution refilling and bus usage can be calculated to be 119 €c/km. The specific cost for a diesel bus was 104 €c/km. Thus the total cost of biomethane use as a vehicle fuel was 14 % higher than the usage of diesel.

In summary, the production cost of biomethane was 9 % more than the current diesel price and the same as the current natural gas price. The costs of usage and maintenance of gas buses were 31 % higher than diesel buses. Total annual costs of gas buses were 19 % higher than in diesel buses. The specific cost for a gas bus was 119 €c/km and for a diesel bus 104 €c/km. Thus, the total cost of biomethane use as a vehicle fuel was assessed to be 14 % higher than for the usage of diesel.

4 LCA – literature assessment

Life cycle assessment reflects ecological impacts, bounded in this assessment as greenhouse gas emissions. The benefits of LCA assessments are numerical values which can be compared to each other in specific cases.

The critical points of LCA assessments are that they are extremely complicated and a challenging task due to the lack of a unique, objective, and commonly agreed methodology. Consequently, the definitions of system boundary, reference scenario, and other assumptions will have a significant impact on the results and are subject to significant uncertainties and sensitivities. Therefore, results from different assessments should be compared only indicatively to each other. (Soimakallio et al. 2009)

This literature assessment was separated into two sections; well-to-tank (WTT) section and tank-to-wheel (TTW) section. The well-to-tank part covered the production of the fuel and bringing it into the fuel storage of the vehicle. Tank-to-wheel described the end-use phase. The principle of the well-to-wheel process is shown in Figure 26.

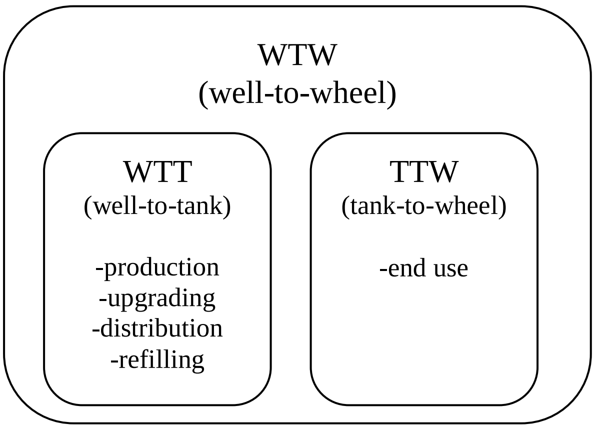

Figure 26. The parts of well-to-wheel process.

4.1 Well-to-tank, WTT

The WTT section includes an overview of the expended energy and the greenhouse gas emission studies. Expended energy versus final fuel energy represents how much energy is needed to get 1 MJ of the fuel.

4.1.1 Expended energy

Figure 27 shows the expended energies and used energy types for fossil fuels like gasoline, diesel and natural gas distributed in different ways. Compressed biogas generated from municipal waste, liquid manure and dry manure are also shown. (Edwards *et al*. 2008, Appendix 2)

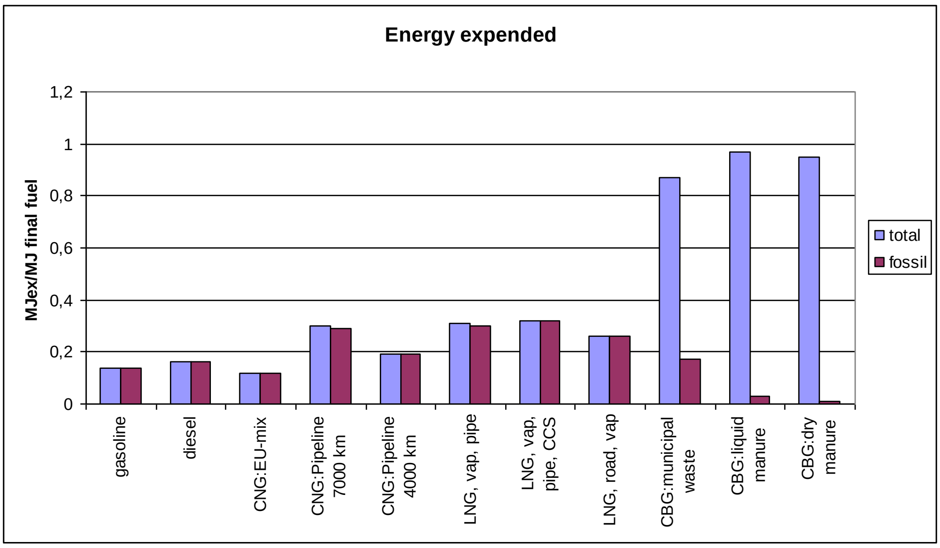

Figure 27. Expended energy versus a final fuel energy, MJex/MJ (Edwards *et al*. 2008, Appendix 2)

As can be seen from the Figure 27, biogas generation and distribution needs on average 0.93 MJ to get 1 MJ of fuel. Respectively, diesel needs 0.16 MJ to get 1 MJ of fuel. Thus, the production and distribution of biogas needs almost six times more energy, but the needed fossil energy is significantly less in manure-based biogases than in fossil fuels.

4.1.2 Greenhouse gas emissions

Greenhouse gas emissions from different substrates are covered from two different points of view. Firstly, greenhouse gas emission estimation results from different studies are listed, and secondly official calculation parameters for such emissions in the European Union according to Directive 2009/28/EC are presented. Directive 2009/28/EC on the promotion of the use of energy from renewable sources (RES) must be implemented in the European Union Member States before 5th December 2010.

According to the RES directive, the greenhouse gas emission saving from the use of biofuels and bioliquids should be at least 35 %. After the beginning of 2017, the greenhouse gas emission saving should be at least 50 % and after the beginning of 2018 that saving should be at least 60 % in installations in which production started on or after 1st Jan 2017.

This assessment was broken down into two sections where the greenhouse gas emission results are presented from different LCA assessments, and the reduction calculations according to RES directive are presented.

4.1.2.1 Emission assessments

Different greenhouse gas emission study sources present the process piece and total emissions for biomethane made from different substrates.

Börjesson *et al*. (2010) studied the Swedish situation of biogas generation from different substrates. The results of the study were as follows: Biogas from ley crops, sugar beets (including tops) and maize are assessed in the current Swedish situation to provide a climate benefit of 86%, 85% and 75%, respectively, compared to fossil fuels. If residues like manure, waste from food industries and organic household waste are used for biogas production they are assessed to provide a climate benefit of 148%, 119% and 103%, respectively, compared to fossil fuels. The reason that the climate benefit exceeds 100% is the indirect effects obtained through increased recycling of nutrients reducing the need for fertilizers, and the increased recycling of organic matter to the soils, etc. As a reference, petrol and diesel were used, having the similar greenhouse gas emissions of 83.8 g CO_2eq/ MJ.

Börjesson and Mattiasson (2007) in Sweden assessed the greenhouse gas emissions of biomethane production from liquid manure. The assessment included substrate storage, biogas generation and upgrading. The given result was -180 g CO_2eq/MJ. In the study, the allocation of the energy input between the fuel and a potential by-product was based on the amount of energy in the biomass substrate that ends up in the fuel and in the by-product. The low result was discussed to be based on the reason that the spontaneous methane emissions were significantly reduced from liquid manure storages.

According to Wetzel (2010), the greenhouse gas emissions during biomethane production were fractioned into six process parts. The assessed substrate mix was 54 % maize, 28 % rye, and 18 % manure. The transportation distance used for the substrate mix was 15 km.

Zah *et al*. (2007) in Switzerland studied greenhouse gas emissions for substrates milk+ whey, manure (covered storages), co-substrate, natural gas and diesel. The studied co-substrate mix included 30 % household wastes and 70 % manure. The results were referred to average values from 2004.

Edwards *et al*. (2008) calculated the greenhouse gas emissions of different fuels for the European Commission, and the values given in RES directive are strongly based on that study. The greenhouse gas emissions for biogas generated from dry manure, liquid manure and municipal waste were calculated. The calculations included all operations required to extract, capture or cultivate the primary energy source. Fossil fuels as "natural gas current EU-mix" and diesel were also studied and their values included the emissions from distribution and filling stations. The natural gas current EU-mix included 1 000 km of transportation.

In Table 12 the results from the above-mentioned studies are shown. The results present the greenhouse gas emissions for substrate storage and possible transportation, biogas generation and upgrading to a biomethane. Also the summarized emissions and specific emissions are calculated. The study results are expressed as g CO_2eq/MJ. The results were calculated to g CO_2eq/km by the author.

Table 12. A combined greenhouse gas emissions for biogas generation and upgrading results of different substrates.

	Substrate+ Transport	Digesting	Upgrading	**Total**	**Specific emission**	
Substrate	g CO_2 e/MJ	g CO_2 e/MJ	g CO_2 e/MJ	**g CO_2 e/MJ**	**g CO_2 e/km***	Source
Maize	6.4			**6.4**	**138**	Börjesson et al. 2010
Wheat	5.8			**5.8**	**125**	Börjesson et al. 2010
Sugar beet	6.6			**6.6**	**143**	Börjesson et al. 2010
Grass	6.1			**6.1**	**132**	Börjesson et al. 2010
Maize + crops	0.09	0.1	0.16	**0.3**	**7**	Wetzel 2010
Milk + whey	0	5	23	**28**	**605**	Zah et al. 2007
Manure cov.	0	-30	15	**-15**	**-324**	Zah et al. 2007
Dry manure	-9	6.3		**-2,8**	**-59**	Edwards et al. 2008
Manure	11.4			**11.4**	**246**	Börjesson et al. 2010
Liq. manure	-94.7	6.3		**-88**	**-1910**	Edwards et al. 2008
Liquid manure	-180			**-180**	**-3888**	Börjesson and Mattiasson (2007)
Industrial waste	8.3			**8.3**	**179**	Börjesson et al. 2010
Municipal waste	0	12.7		**12.7**	**274**	Edwards et al. 2008

Household waste		11.2		**11.2**	**242**	Börjesson et al. 2010
Cosubstrate	0	-22	15	**-7**	**-151**	Zah et al. 2007
Natural gas	11	0	0	**11**	**238**	Zah et al. 2007
NG current EU-mix		8.7		**8.7**	**188**	Edwards et al. 2008
Diesel		14.2		**14**	**231**	Edwards et al. 2008
Diesel/petrol		83.8		**83.8**	**1361**	Börjesson et al. 2010
Diesel	11	3**	0	**14**	**227**	Zah et al. 2007

* Calculated

** Refining

As can be seen from Table 12, the results vary among the different studies. The lowest emissions of generated biomethane were assessed to be from liquid manure, and the highest from milk and whey. The variation for biomethane generated from crops was between 7 and 143 g CO_2eq/km. The variation for biomethane generated from manures were between -3 888 and 246 g CO_2eq/km. The variation for biomethane generated from industrial and municipal wastes was between -151 and 274 g CO_2eq/km. These variations may be due to, e.g. different calculation parameters for residues and assumed emission reductions.

Wetzel (2010) presented the greenhouse gas emissions for distribution by gas pipeline as 3.6 g CO_2eq/MJ, which equals 78 g CO_2eq/km. Emissions from refilling were reported to be 0.33 g CO_2eq/MJ, equal to 7 g CO_2eq/km.

Edwards *et al*. (2008) presented the greenhouse gas emissions for the refilling as 2.9 g CO_2eq/MJ, equal to 62 g CO_2eq/km. Separate emission results from diesel distribution and refilling were reported to be 1 g CO_2eq/MJ, equal to 22 g CO_2eq/km.

As an example, the total greenhouse gas emissions are assessed for biomethane generated from dry manure, distributed to a filling station via gas pipeline and refilled to buses. The emission values for the process for biomethane and refilling assessed by Edwards *et al*. (2008) were used. The calculation is shown in Table 13. In the comparison of the result from the example with emissions of the natural gas current EU-mix (188 g CO_2eq/km), the biomethane from dry manure produces 57 % less CO_2eq/km. A comparison of the result with diesel (231 g CO_2eq/km) shows the reduction was 65 %.

Table 13. Well-to-tank emission example for dry manure.

	Emission	Specific emission
Process stage	g CO_2 e/MJ	g CO_2 e/km*
Processing to biomethane	-2.8	-59
Distribution by pipeline	3.6	78
Filling station	2.9	62
Total	**3.7**	**81**

* Calculated

4.1.2.2 RES directive

According to Directive 2009/28/EC (European Council 2009) on the promotion of the use of energy from renewable sources (so-called RES directive) the greenhouse gas emission saving from the use of biofuels and bioliquids will be officially calculated using default greenhouse gas emission saving percentages given by the RES directive. Operators are always able to use actual greenhouse gas emission values but those values must be verified. Operators can also use default emission values to show observation of the sustainability criteria set for biofuels and bioliquids. However, the default values for biofuels, and the disaggregated default values for cultivation may be used only when their raw materials are:

- cultivated outside the European Union;
- cultivated in the European Union in areas included in the lists referred to in paragraph 2[13]; or
- waste or residues other than agricultural, aquaculture and fisheries residues.

Emission calculations

The RES directive stipulates how greenhouse gas emissions from the production and use of transport fuels, biofuels and bioliquids must be calculated. Greenhouse gas emissions from fuels, E, shall be expressed in terms of grams of CO_2 equivalent per MJ of fuel, gCO_2eq/MJ. The calculations are done with the formula:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee}$$

where

E = total emissions from the use of the fuel

e_{ec} = emissions from the extraction or cultivation of raw materials

[13] By 31 March 2010, Member States submitted to the Commission a report including a list of those areas on their territory classified as level 2 in the nomenclature of territorial units. The typical greenhouse gas emissions from cultivation of agricultural raw materials can be expected to be lower than or equal to the emissions reported under the heading 'Disaggregated default values for cultivation' in part D of Annex V to RES Directive, accompanied by a description of the method and data used to establish that list. That method shall take into account soil characteristics, climate and expected raw material yields.

e_l = annualized emissions from carbon stock changes caused by land-use change
e_p = emissions from processing
e_{td} = emissions from transport and distribution
e_u = emissions from the fuel in use
e_{sca} = emission saving from soil carbon accumulation via improved agricultural management
e_{ccs} = emission saving from carbon capture and geological storage
e_{ccr} = emission saving from carbon capture and replacement
e_{ee} = emission saving from excess electricity from cogeneration

Annualized emissions from carbon stock changes caused by land-use change, e_l, shall be calculated by dividing total emissions equally over 20 years. For the calculation of those emissions the following rule is applied:

$$e_l = (CS_R - CS_A) \times 3.664 \times 1/20 \times 1/P - e_B$$

The quotient obtained by dividing the molecular weight of CO_2 (44.010 g/mol) by the molecular weight of carbon (12.011 g/mol) is equal to 3.664, where

e_l = annualized greenhouse gas emissions from carbon stock change due to land-use change (measured as mass of CO_2-equivalent per unit biofuel energy)
CS_R = the carbon stock per unit area associated with the reference land use (measured as mass of carbon per unit area, including both soil and vegetation). The reference land use shall be the land use in January 2008 or 20 years before the raw material was obtained, whichever was the later
CS_A = the carbon stock per unit area associated with the actual land use (measured as mass of carbon per unit area, including both soil and vegetation). In cases where the carbon stock accumulates over more than one year, the value attributed to CSA shall be the estimated stock per unit area after 20 years or when the crop reaches maturity, whichever the earlier
P = the productivity of the crop (measured as biofuel or bioliquid energy per unit area per year)
e_B = bonus of 29 g CO_2eq/MJ biofuel or bioliquid if biomass is obtained from restored degraded land under the conditions provided for in point 8 (European Council 2009, page 54).

Default emission values for the cultivation, processing, transporting and distributing of biomethane made from municipal waste, dry manure and wet manure are presented in the RES directive. The disaggregated default emission values and thus calculated total default greenhouse gas emissions are shown in Table 14. The default emission values of biomethane are presented only for processing, transportation and distribution. Emission from the fuel in use, e_u, is presented to be zero for biofuels and bioliquids.

Table 14. Default greenhouse gas emissions for biomethane made from municipal waste, wet manure and dry manure according to RES directive (European Council 2009).

		Municipal waste	Wet manure	Dry manure
		g CO_2eq/MJ	g CO_2eq/MJ	g CO_2eq/MJ
Cultivation	e_{ec}	0	0	0
Processing	$e_p - e_{ee}$	20	11	11
Transport + distribution	e_{td}	3	5	4
Sum		**23**	**16**	**15**

In summary, the results of WTT assessment have large variations depending on the source referred to. The variation represents a common situation in LCA studies because system boundaries, limitations and different allocations are not standardized. However, indicatively it can be summarized that biomethane production from manures effectively save greenhouse gas emissions.

4.2 Tank-to-wheel, TTW

A heavy-duty vehicle does not have legal test methods and requirements for fuel consumption and emission measurements for complete vehicles. Therefore comparable fuel consumption and emission results for different bus types does not exist. (Nylund, Erkkilä, Hartikka 2007)

Standardized emission certification methods for heavy-duty applications are nowadays based on stand-alone engine tests on engine dynamometers. However, engine testing does not account for the properties of the vehicle itself (vehicle weight, drive train, body structure, cooling system arrangement, etc.). Testing complete vehicles on a chassis dynamometer has resolved many problems, and vehicle testing has generated reliable specific emissions in grams per kilometre instead of per kilowatt-hour. Currently, no legal requirements to carry out testing using a chassis dynamometer exist. (Nylund, Erkkilä, Clark, Rideout 2007)

Tests of heavy-duty vehicles on a chassis dynamometer simulates "real-life" emission and fuel consumption figures (g/km-based), the effects of payload and driving cycle, and vehicle-to-vehicle comparisons, and checking of in-use vehicles. The most commonly used test cycle is the transient type cycle using the German Braunschweig city bus cycle. (Nylund 2010)

Fuel consumption

According to the VTT database (Nylund 2010), the emissions of tested buses are shown in Table 15. The results shows that g CO_2eq/km emissions from CNG EEV buses average 16 % higher compared to diesel EEV buses. Fuel consumptions are based on the results seen in Table 14. For CNG EEV, the fuel consumption was 0.462 kg/km / 0.73 kg/Nm^3 / 0.97 = 0.6 Nm^3/km. Gas fuel consumptions did not vary between lean-burn spark ignition engines and stoichiometric engines (Hartikka 2010). For the diesel bus, the used fuel consumption in the calculations was an average of Euro V and EEV bus results. Thus the fuel consumption was 0.375 kg/km / 0.84 kg/l = 0.45 l/km.

Table 15. Averages of emissions and fuel consumptions measured with chassis dynamometer in VTT. Braunschweig city bus cycle. (Nylund 2010)

Braunschweig-cycle		CO	HC	CH4*	NOx	PM	CO_2	CO_2 eq	FC	FC
		g/km	g/km	g/km	g/km	g/km	g/km	g/km	kg/100km	MJ/km
Diesel	Euro 1	1.39	0.32	0	15.6	0.436	1219	1219	38.6	16.4
Diesel	Euro 2	1.48	0.19	0	12.9	0.202	1270	1270	41	17.4
Diesel	Euro 3	0.8	0.14	0	8.6	0.195	1189	1189	38.2	16.2
Diesel	Euro 4	2.84	0.1	0	8.4	0.112	1194	1194	38.5	16.4
Diesel	Euro 5**	2.84	01	0	8.4	0.087	1194	1194	38.5	16.4
Diesel	EEV	1.12	0.02	0	5.9	0.062	1116	1116	36.4	15.5
CNG	Euro 2	4.32	7.12	2.33	16.9	0.009	1128	1283	42.1	20.1
CNG	Euro 3	0.14	1.67	1.14	9.4	0.011	1257	1295	46.2	22
CNG	EEV	2.27	1.04	0.87	3.2	0.007	1275	1294	46.3	22.7

* For diesel CH4 = 0
** Euro 5 emission factors are estimated by Euro 4 results
PM = Particle emission
FC = Fuel consumption

Emissions

This assessment covered primarily the greenhouse gas emissions, but other main emissions were also listed, although no further calculations on them were made.

Greenhouse gas emissions from bus usage mainly followed the fuel consumptions. The main difference between gas and diesel buses was the methane emission from the gas buses, which increased the g CO_2eq/km emissions. In a comparison between diesel EEV and CNG EEV buses, emissions shown in Table 14, the gas bus gave 16 % more greenhouse gas emissions.

Particle emissions from the CNG EEV bus were measured to be 0.007 g/km and from the diesel EEV 0.062 g/km. Thus the particle emission reduction of gas bus was 89 % compared to the diesel bus.

Nitrogen oxide emissions from the CNG EEV bus were measured to be 3.18 g/km and from the diesel EEV 5.87 g/km. Thus the nitrogen oxide emission reduction of the gas bus was 46 % compared to the diesel bus.

Carbon monoxide emissions from the CNG EEV bus were measured to be 2.27 g/km and from the diesel EEV 1.12 g/km. Thus the nitrogen oxide emission increase of gas bus was 103 % compared to the diesel bus.

In summary, the natural gas buses produced 16 % more greenhouse gas emissions compared to diesel buses due to their higher fuel consumption.

4.3 Well-to-wheel, WTW

The summarized greenhouse gas emissions from well-to-tank and tank-to-wheel section based on the referred studies were calculated. The total variations for usage of biomethane from different substrates are shown in Table 16. The listed variations were compared with the results of natural gas and diesel, and the emission reductions were calculated. The calculation was made, for example, for crops compared to natural gas as follows; -((7 - 1482) / 1482) * 100 = 99.5 %. Because biomethane is a biofuel, the end-use emission was considered to be carbon neutral.

Table 16. Well-to-wheel emission variations and reductions for biomethane from dry manure, natural gas and diesel.

	Biomethane			Natural gas, EU-mix	Diesel
	Crops	Manures	Industrial and municipal wastes	Specific emission	Specific emission
	g CO_2eq/km	g CO_2eq/km	g CO_2eq/km	g CO_2eq/km	g CO_2eq/km
WTT	7 - 143	-3888 - 246	-151 - 274	188*	231*
TTW	0	0	0	1294*	1116*
WTW	7 - 143	-3888 - 246	-151 - 274	1482	1347
r.c.NG	99.5 – 91 %	354 - 84 %	110 - 82 %		
r.c. D	99.5 - 89 %	389 - 82 %	111 - 80 %		

* Edwards et al. 2008
r.c. NG = reduction compared to natural gas
r.c. D = reduction compared to diesel

As can be seen from Table 16, according to different LCA studies biomethane generated from crops reduced on average 95 % (average of 99.5 and 91) and 94 % the greenhouse gas emissions from natural gas and diesel powered buses, respectively. Biomethane generated from manures reduced emissions respectively by an average of 223 % and 235 %. Biomethane generated from industrial and municipal wastes reduced emissions respectively by an average of 96 % and 95 %. Therefore, the most potential greenhouse gas emission saving substrate is manures, then industrial and municipal waste and finally crops.

According to the RES directive (European Council 2009), the greenhouse gas emission saving from biofuels and bioliquids must be calculated as follows:

SAVING = $(E_F - E_B)/E_F$

where
E_B = total emissions from the biofuel or bioliquid
E_F = total emissions from the fossil fuel comparator

The default emission value for fossil fuel comparator, E_F, is also set in the RES directive. The value used is average emissions from the fossil part of petrol and diesel, 83.8 g CO_2eq/MJ.

The default emission saving values for biofuels for upgraded biogases made from municipal waste, wet manure and dry manure were calculated using the default emission values seen in Table 14, and set as follows:

- from municipal organic waste as compressed natural gas 73 % ((83.8 – 23) gCO_2eq/MJ / 83.8 gCO_2eq/MJ = 0.73 → 0.73 * 100 = 73 %)
- from wet manure as compressed natural gas 81 %
- from dry manure as compressed natural gas 82 %

By comparing the greenhouse gas emission saving results according to the RES directive and the calculations based on different LCA study sources the similarity can be seen where manures have better emission saving potential than municipal waste. Because the RES directive is strongly based on emission estimations made by Edwards *et al*. (2009) it can be estimated that biomethane made from crops gives an emission saving potential of lower than or at the same level as municipal waste set by the RES directives.

In summary, the greenhouse gas emission saving varied and was dependent on the substrate used and on the data source. Emission savings according to the RES directive were much less than calculated from different literature sources. According to the RES directive, the greenhouse gas emission saving for biomethane made from manures is about 82 % and 73 % if made from municipal waste. The greenhouse gas emission default values set by the RES directive are the official values and therefore these should be used in further discussions.

5 Sensitivity assessment

Sensitivity assessment was a critical review of this assessment and the section was broken down into two sections covering life cycle costs and life cycle assessment.

5.1 LCC

The cost calculations were mostly based on Swedish studies, thus the results may reflect more the situation in Sweden. On the other hand, in Sweden biogas generation and vehicle use are commonly used and thus the results can be quite reliably generalized.

The influence of different substrates on the variation of costs was not very well covered. For example, the cost of crops varies, but in this case the price of crop was assumed to be free.

The substrate of a biogas generation affects the biogas generation costs by needing different handling equipments, transportation and storage. Cost variations caused by different substrates were not well covered in this assessment, but it gives an indicative result that biogas generation from wastes and manure is more economical than generation from grains. Generally, it can be suggested that calculations for a biogas generation costs should be done separately for each planned plant. The costs for upgrading and distribution of biomethane can be generalized more easily than the costs of biogas generation.

Upgrading costs were assessed mostly for commercially based methods for raw gas capacity over 500 Nm^3/h, and the costs for emerging and small-scale upgrading techniques were not reliably included in this assessment.

Distribution costs had a large variation especially in pipeline distribution. The shown costs were based on values from high cost level countries. Thus, the costs of pipeline installation and maintenance can be notably less than shown in this assessment.

Digestate handling and reselling were not included in this assessment. However, the sales of digestate decreases the minimum price caused by the production and distribution costs of biomethane. On the other hand, if the quality of the digestate is poor and it cannot be sold for use as fertilizer, it must be disposed of, e.g. in landfill, which brings costs.

Varying diesel and natural gas prices in different countries gives more opportunities to choose the most economical fuel. Calculating with a natural gas price of 0.6 €/Nm^3 (0.82 €/kg) the total specific costs equals diesel-powered buses, and vice versa, the diesel price can rise to 1.3 €/litre to reach the same specific cost of biomethane buses.

5.2 LCA

Well-to-tank (WTT) results from the referred studies had a large variation due to differences in system boundaries and limitations. On the other hand, the emission results showed indicatively that waste-based substrates give a better greenhouse gas emissions saving value than non-waste-based substrates.

There was a lack of emission results from methane distribution by vehicles, and therefore it was not included in this assessment. A discussion of how fugitive the emissions are from vehicle distribution, and how those emissions could be quantitatively measured should take place.

The tank-to-wheel (TTW) emission results are based on the measurements made by VTT. Fuel consumptions in this assessment also based on the same results using the German Braunschweig city bus cycle. The Braunschweig city bus cycle is only one of the commonly used test cycles. Thus, in real life the fuel consumptions and emissions vary depending on the driven cycle length, number of accelerations and delays, and driver's habits, etc.

WTT emissions for natural gas and diesel fuels were from different studies, and therefore a comparison of emissions from biomethane usage with those emissions produced various uncertainties.

6 Conclusions

The specific cost results for gas and diesel buses using biomethane or diesel as a vehicle fuel are shown in Figure 28. The life cycle cost inventory results can be listed also as follows;

- Biogas generation, upgrading, distribution and refilling cost with a raw gas capacity of 1 000 Nm^3/h was 49 €c/km, which was 9 % more expensive than diesel fuel.
- Content of the specific cost above was biogas production 43 %, upgrading 14 %, distribution via CMG trailer 6 % and refilling 37 %.
- The investment cost of a EURO V certified gas bus was 17 % higher than diesel bus.
- Maintenance and usage specific costs of the gas buses were calculated to be 24 €c/km, which was 31 % higher than in diesel buses.
- The total annual specific costs of the gas buses were calculated to be 70 €c/km, which was 19 % more than annual costs of diesel buses.

- Biomethane usage as a vehicle fuel in gas buses was calculated to give the specific cost of 119 €c/km, which was 14 % more than diesel fuel powered buses.

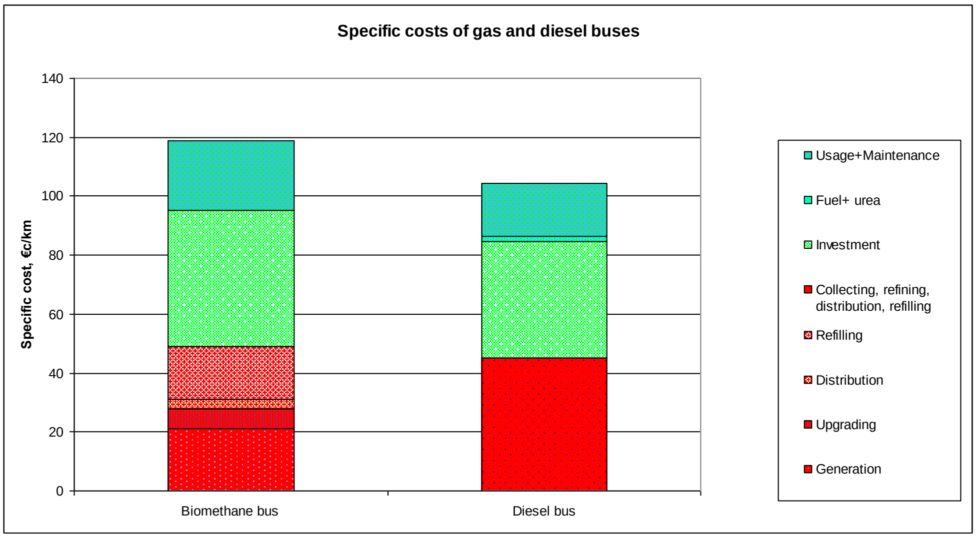

Figure 28. The specific costs of biomethane and diesel buses.

The specific emission results of well-to-wheel chain for natural gas, diesel and biomethane made from different substrates are shown in Figure 29. The life cycle assessment inventory results can be listed also as follows;

- The fuel consumption of gas buses was 23 % more than in diesel buses.
- Well-to-tank specific emissions of biomethane generated from crops varied between 7 and 143 g CO_2eq/km; biomethane generated from manures varied between -3 888 and 246 g CO_2eq/km and biomethane generated from industrial and municipal wastes varied between -151 and 274 g CO_2eq/km.
- Tank-to-wheel greenhouse gas emission from a natural gas bus was 16 % more than from a diesel bus due to higher fuel consumption.
- Well-to-wheel greenhouse gas emission saving values will be officially calculated using the RES directive.
- The RES directive gives the default greenhouse gas emission saving value of 73 % for biomethane generated from municipal waste versus diesel buses.
- The default greenhouse gas emission saving values for wet and dry manures were 81 % and 82 %, respectively.
- The best savings of greenhouse gas emissions were achieved with manure-based biomethane.

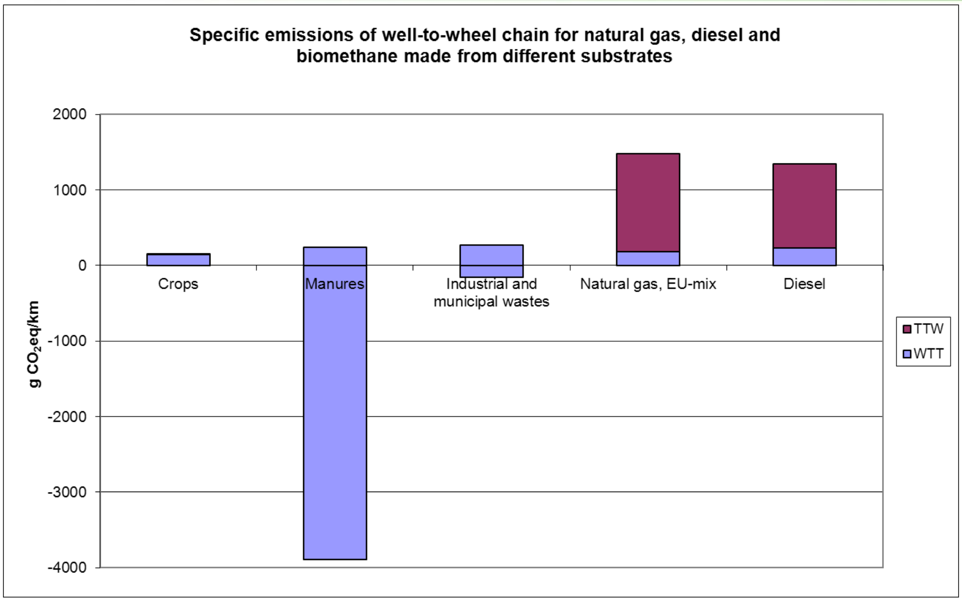

Figure 29. The specific emissions of natural gas, diesel and biomethane made from different substrates.

Conclusions and recommendations based on this assessment were as follows;

- Biomethane production costs should be reduced to reach the diesel cost. Cost reduction may be achieved by substrate and technology selection, for instance using low-cost substrates (often waste-based), by reducing substrate and digestate handling facilities, etc.
- Economical profitability depends on biogas production capacity, however, the dependency is not very strong on a raw gas capacity of 1 000 Nm^3/h.
- Investment and maintenance costs of gas buses should become less expensive to meet the costs of diesel buses. This might be achieved for instance using national subsidies for renewable energies and the development of engine technologies.
- In the future, to reach the emission requirements of EURO VI certification, the costs of diesel buses after assumed actions and their estimated costs, the usage of diesel buses pays still less than gas bus usage.
- High greenhouse gas emission savings can be achieved using manures and wastes as a substrate for biogas.

Socio-economical factors (environmental costs) are not included in this study. They are real costs for the society and estimated costs for different emissions can be found but at least at the moment those costs are not realized for fleet owners. Environmental costs are included in the reports 3.1 Manual for strategy, policy and action plan “How to introduce biogas buses” and 6.8 Feasibility study to introduce biogas buses in Tartu, Estonia.

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Appendix 1

BIOGAS GENERATION AND UPGRADING COSTS

Table 1. Biogas generation costs.

Biogas generation		Capacity	Investment	Annual costs			Investment	Usage	Total	Total	**Generation**
		rawgas		capital	usage	total	€c/Nm^3	€c/Nm^3	€c/Nm^3	€c/Nm^3	**Total**
source	main substrate	Nm^3/h	k€	k€	k€	k€	rawgas	rawgas	rawgas	97% CH_4	**€c/km**
Urban et al. 2009	manure	100	535,1	55	162	217	6,6	20	26	42	**25**
Urban et al. 2009	manure	250	1080	111	403	514	5,4	19	25	40	**24**
Urban et al. 2009	manure	500	1850	190	737	927	4,6	18	22	36	**22**
Held et al. 2008	pig manure	183	2000	206	103	309	13,6	7	20	33	**20**
Held et al. 2008	sewage sludge	400	4000	412	206	618	12,4	6	19	30	**18**
Held et al. 2008	foodwaste	38	400	41	21	62	13,0	7	20	32	**19**
Held et al. 2008	sewage sludge	1617	7200	741	371	1112	5,5	3	8	13	**8**
Held et al. 2008	sewage sludge	1142	8800	906	453	1359	9,6	5	14	23	**14**
Urban et al. 2009	maiss	250	1375	142	534	676	6,8	26	33	53	**32**
Urban et al. 2009	maiss	500	2450	252	1026	1278	6,1	25	31	50	**30**
Urban et al. 2009	maiss	1000	4400	453	1998	2451	5,5	24	30	48	**29**
Urban et al. 2009	maiss	1500	6188	637	2937	3574	5,1	24	29	46	**28**
Urban et al. 2009	maiss	2000	7900	813	3876	4690	4,9	23	28	46	**27**

Table 2. Biogas upgrading cost.

Upgrading		Capacity	Investment	Annual costs			Investment	Usage	Total	Total	**Upgrading**
		rawgas		capital	usage	total	€c/Nm^3	€c/Nm^3	€c/Nm^3	€c/Nm^3	**Total**
method	source	Nm^3/h	k€	k€	k€	k€	rawgas	rawgas	rawgas	97% CH_4	**€c/km**
Water wash	Urban et al. 2009	250	1145	118	111	229	6	6	11	18	**11**
	Urban et al. 2009	500	1324	136	190	327	3	5	8	13	**8**
	Urban et al. 2009	1000	1699	175	348	523	2	4	6	10	**6**
	Pulsa 2008	350	1178	121	133	254	4	5	9	14	**8**
	Pulsa 2008	1400	3940	406	355	760	3	3	7	11	**6**
	Lappalainen 2010	1000	1900	196	115	311	2	1	4	6	**4**
	Benjaminsson et al. 2007	5700	9000	927	905	1832	2	2	4	6	**4**
	Pulsa 2008	160	1600	165	87	252	12	7	19	31	**18**
	Pulsa 2008	220	1900	196	103	299	11	6	16	26	**16**
	Pulsa 2008	440	2700	278	162	440	8	4	12	19	**12**
	Pulsa 2008	1200	4300	443	400	843	4	4	8	14	**8**
PSA	Urban et al. 2009	500	1408	145	191	336	3	5	8	13	**8**
	Urban et al. 2009	1000	1841	190	350	539	2	4	6	11	**6**
	Urban et al. 2009	2000	2925	301	681	982	2	4	6	10	**6**
	Urban et al. 2009	500	1069	110	228	338	3	6	8	13	**8**
	Pulsa 2008	5000	9417	970	1185	2155	2	3	5	8	**5**
	Pulsa 2008	5000	12600	1297	2200	3497	3	5	8	14	**8**
	Held et al. 2008	400	1500	154							
	Held et al. 2008	400	2500	257							
Chemical	Urban et al. 2009	500	996	103	261	363	2	6	9	14	**8**
Scrubbing	Urban et al. 2009	250	847	87	120	207	4	6	10	16	**10**
	Urban et al. 2009	500	1057	109	224	333	3	5	8	13	**8**
	Urban et al. 2009	1000	1556	160	410	571	2	5	7	11	**7**
	Björkman, email 2010	750	2010	207	226	433	3	4	7	11	**7**
	Benjaminsson et al. 2007	6280	8600	885	800	1685	2	2	3	5	**3**
Cryo	Petersson 2009, p 45	1000	4760	490	760	1250	6	9	15	24	**15**
	Petersson 2009, p 45	1000	9960	1026	1020	2046	12	12	25	40	**24**
	Petersson 2009, p. 45	1000	6670	687	1250	1937	8	15	23	38	**23**
	Benjaminsson et al. 2007	5700	5700	587	635	1222	1	1	3	4	**3**
	Pulsa 2008	100	1300	134	135	269	16	16	32	52	**31**
	Pulsa 2008	250	1500	154	188	342	7	9	17	27	**16**
	Pulsa 2008	110	580	60	22	82	7	2	9	14	**9**
	Pulsa 2008	440	810	83	77	161	2	2	4	7	**4**
	Pulsa 2008	4400	3880	399	722	1121	1	2	3	5	**3**

Appendix 2

DISTRIBUTION COSTS

The costs of distribution by local pipeline and by vehicles for the biomethane capacity of 600 Nm^3/h (5 MNm^3/a). The costs of pipeline distribution are given in Table 1 and the costs of vehicle distributions are given in Table 2.

Table 1. The distribution costs by local pipeline.

	Pipe line distance	capacity 97% CH_4	Investment cost	Annual costs				Costs per Nm^3				Total cost	Spesific cost
				capital cost	usage	maintenance	compressing	investment	usage	maintenance	compressing		
	km	Nm^3/h	k€	k€	k€	k€	k€	€c/Nm^3	€c/Nm^3	€c/Nm^3	€c/Nm^3	€c/Nm^3	€c/km
	20	600	1880	194	150	19	548	4	3	0	11	18	11
Rural	100	600	9400	968	752	94	548	19	15	2	11	47	28
	200	600	18800	1936	1504	188	548	39	30	4	11	84	50
	20	600	5400	556	432	54	548	11	9	1	11	32	19
Urban	100	600	27000	2780	2160	270	548	56	43	5	11	116	69
	200	600	54000	5560	4320	540	548	112	87	11	11	220	132

Table 2. The distribution costs by vehicle.

Distribution by vehicle		CMG			LMG	
	source	Sweco 2005	Sweco 2005	Mathiasson 2009	Hansson 2008	Mathiasson 2009
Investment costs	unit	Hook lift	trailer	swap body	LNG 21 ton	LNG 21 ton
Volume/piece	Nm^3	1900	6000		32000	32000
Pieces		3	1		1	
Total volume	Nm^3	5700	6000		26250	
Capacity	ton	4.8	5	1.8	21	21
Unit price	€/piece	50000	150000		270000	
Investment	€	150000	150000		270000	
Annual capital cost	€	15444	15444		27800	
Capital cost	€c/Nm^3	0.31	0.31		0.56	
Operation						
Hourly price	€/h	80	45		55	
Load+upload time	h	1	3		4	
1 load	€	240	135		220	
Load	€c/Nm^3	4.2	2.3		0.8	
Loads/year	piece	874	830		190	
Cost/year	k€	210	112		42	
Distance and driving time costs						
20 km, 0.5 hours	€	320	180		275	
100 km, 1.5 hours	€	480	270		385	
200 km, 3 hours	€	720	405		550	
Total specific costs						
20 km	€c/Nm^3	10	6	10	2.4	2
100 km	€c/Nm^3	13	7	17	2.8	4
200 km	€c/Nm^3	17	9	30	3.5	6
20 km	€c/km	6	3	6	1.5	1.2
100 km	€c/km	8	4	10	1.7	2.4
200 km	€c/km	10	6	18	2.1	3.6

Appendix 3

FILLING STATION AND BUS USAGE COSTS

Table 1. Filling station costs

Filling stations		Capacity biomethane	high pressure dispencers	low pressure dispencers	Investment	Annual costs				Investment	Usage + maintenance	Total	**Specific cost**
						capital	usage	maintenance	total				
	source	Nm^3/day	pieces	pieces	k€	k€	k€	k€	k€	€c/Nm^3	€c/Nm^3	€c/Nm^3	**€c/km**
Bus depot	Sweco 2005	3600		50	2000	206	63	16	285	16	5	22	**13**
	Vainikka 2010	6850	2	50	1200	124	250		374	5	10	15	**9**
	Ferré et al 2009	5000		50	650	67	19	100	186	4	1	10	**6**
	Ferré et al 2009	8000		100	1000	103	29	154	286	4	1	10	**6**
	Ferré et al 2009	4100	2	150	1791	184	51	277	512	12	3	34	**21**
Fast filling	Vainikka 2010	4800	2	-	600	62	254		316	4	20	18	**11**
	Biogas Öst 2008	3000	2	-	200	21	230		251	2	21	23	**14**
	Biogas Öst 2008	70	2	-	140	14			14	56		56	**34**
	Biogas Öst 2008	1900	2	-	890	92			92	13		13	**8**

Table 2. Bus costs according to manufacturers and increased diesel fuel consumption

					Investment		Annual costs							Spesific costs			**Total**
				Fuel cons.	bus	aftertr.	capital	fuel	urea	usage	maintenance	pick-up	total	Investment	Fuel+ urea	Usage+M	
Fuel	certificate	combustion	Aftertr.	l/km	k€	k€	k€	k€	k€	k€	k€		k€	€c/km	€c/km	€c/km	**€c/km**
Diesel	EURO IV, V	spark-ignition	SCR	0.45	230		24		0.7	10.8			35	39	1	18	**59**
Diesel	EURO VI	spark-ignition	SCR+DPF	0.46	230	6.5	24	0.6	0.7	11.7			37	41	2	18	**61**
				Nm^3/km													
CMG	EURO V	spark-ignition	SCR	0.6	288		30		0.7	13.5		0.1	44	49	1	23	**73**
CMG	EURO V	stoichiometric	TWC	0.6	250		26			14.8		0.1	41	43		25	**68**

Appendix 4

COST UPDATE TO YEAR 2012

The specific cost results detailed in the assessment were updated from year 2010 to 2012. Custom price of Diesel in Finland was increased from 1.1 €/l to 1.5 €/l. Bus operators can get max. 10 % discount of the diesel price, thus the price used in calculations was increased from 1 €/l to 1.4 €/l. All other costs were increased with 6.4 %, due to inflation in Finland. Inflation from year 2010 to 2011 was 3.4 % and in months 1-6/2012 it was 3 %.

The updated specific cost of fuel for biomethane was 52 €c/km (year 2010 it was 49 €c/km) and for diesel 63 €c/km (45 €c/km). The updated total specific cost results in year 2012 for biomethane bus was 126 €c/km (119 €c/km) and for diesel bus 127 €c/km (104 €c/km). Results from year 2010 and 2012 are shown in Figure 1 and in Table 1.

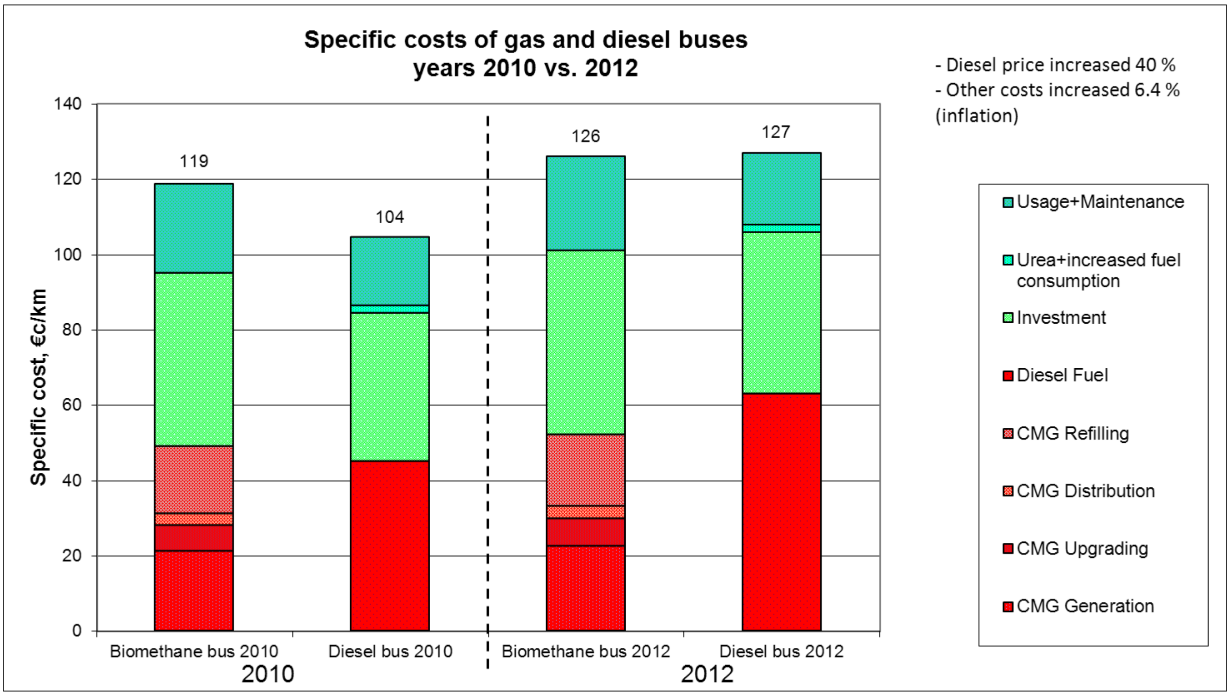

Figure 1. The specific cost results of biomethane buses and diesel buses from year 2010 and updated results from year 2012.

Table 1. Separated specific cost results from years 2010 and 2012.

€c/km	2010		2012	
	Biomethane bus	Diesel bus	Biomethane bus	Diesel bus
CMG Generation	21		22.3	
CMG Upgrading	7		7.4	
CMG Distribution	3		3.2	
CMG Refilling	18		19.2	
Diesel Fuel		45		63
Investment	46	39	49	43
Urea+increased fuel consumption	0	2	0	2
Usage+Maintenance	24	18	25	19
sum	119	104	74	127

The updated results show that total specific costs of diesel and biogas buses are at the same level. The main balancing reason was notably increased diesel price.