Biogas as vehicle fuel - **Ma**rket E**x**pansion to 2020 Air Quality

Contract Number: 019795

Report on Technological Applicability of Existing Biogas Upgrading Processes

Deliverable D3.1 – Report

Work Package 3 – Upgrading

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Abstract:

This report deals with the topic of biogas upgrading to vehicle fuel quality. It is divided into two complementary parts:

Part 1: The upgrading plants of Stockholm. Lille and Rome are here described. The main experiences of several years of operation in Stockholm and Lille have also been compiled.

Part 2: This is a brochure produced by IEA Task 37 and BIOGASMAX in co-operation. It will be produced as a quality print product for dissemination purposes.

Part 2 gives a broad overview of biogas upgrading and utilisation, whereas Part 1 gives more details from some of the sites.

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PREFACE

This report deals with the topic of biogas cleaning and upgrading to vehicle fuel quality. Cleaning is used for technologies and measures with the purpose to reduce the content of emissions such hydrogen sulphide (H_2S) and halogenated hydrocarbons in the biogas. Upgrading is used for technologies and measures with the purpose to reduce the content of carbon dioxide (CO_2) in the biogas.

The report is divided into two complementary parts:

Part 1:

This is a brochure about biogas cleaning and upgrading technologies, produced by IEA Task 37 and BIOGASMAX in co-operation. It will be produced as a quality print product for dissemination purposes.

The report has been written by SGC (Swedish Center for Gas Technology) and Nova Energie.

Part 2:

The upgrading plants of Stockholm and Gothenburg, Sweden, Bern, Switzerland, Lille, France, and Rome, Italy, are here described.

The main experiences of several years of operation in Stockholm, Lille and Rome have also been compiled.

Annexed to the report are also three matrices in which the commonly used upgrading technology today, as well as “new” probably coming technologies are compared with each other in general and from a technical and economical point of view.

This report has been written by a consultant assigned by the City of Stockholm, with important input from the BIOGASMAX sites

Part 1 gives a broad overview of biogas upgrading and utilisation, whereas Part 2 gives more details from some of the sites.

Summary

Present report is the result of a co-operation project between BIOGASMAX and IEA Task 37 concerning cleaning and upgrading of raw bio-based methane (anaerobic digestion of biomass or landfill gas) to so called upgraded biogas for us in (first hand) vehicle purposes. Cleaning is in the report used for technologies and measures with the purpose to reduce the content of emissions such hydrogen sulphide (H_2S) and halogenated hydrocarbons in the biogas. Upgrading is in the report used for technologies and measures with the purpose to reduce the content of carbon dioxide (CO_2) in the biogas.

Part 1 has been written by SGC (Swedish Center for Gas Technology) and Nova Energie whereas part 2 has been written by a consultant assigned by the City of Stockholm, with important input from the BIOGASMAX sites

Part 1

In the report are biogas related issues such as:

- Biogas composition.
- Contaminants in biogas.
- National and international gas standards
- Gas utilisation

described.

However, the main part of the report is focusing on upgrading and cleaning technologies.

Upgrading technologies discussed and partly described in the report are:

- Physical absorption (scrubbing with liquid)
- Chemical absorption (chemical reaction with a liquid)
- Pressure swing adsorption (adsorption on adsorption material like activated carbon)
- Membrane separation
- Cryogenic separation (cooling at elevated pressure)
- In-situ enrichment (sludge treatment)

Cleaning technologies are discussed and partly described related to the main impurities that can be found in biogas such as:

- Sulphur
- Halogenated hydrocarbons
- Organic silicon compound
- Oxygen and nitrogen
- Water

Upgrading

Physical absorption is based on a process and a liquid in which impurities are more soluble than methane. Water scrubbing is the most commonly used technique to remove carbon dioxide as well as sulphur dioxide from biogas. The water could be regenerated or not. Water scrubbing without regeneration is most common at sewage treatment plants where cheap water can be found. Another solvent that can be used for physical absorption is polyethylene glycol. When dealing with chemical absorption the process I similar but then the carbon dioxide is removed from the gas through a chemical reaction with a liquid such as alcanol amines. In this case the liquid is always regenerated.

In pressure swing adsorption (PSA), carbon dioxide is adsorbed on a material like activated carbon or molecular sieves. The selectivity of the adsorption depends on the mesh sizes. PSA takes place at elevated pressure and the material is regenerated through reducing the pressure. Impurities such as water and hydrogen sulphide needs to be pre separated before the gas is fed into the adsorption vessel since they otherwise poison the material irreversibly.

Membrane separation of carbon dioxide from biogas can be outlined in two ways. Either it is a separation with gas phase on both sides of the membrane or it is a gas-liquid absorption which means that a liquid absorbs the carbon dioxide diffusing through the membrane. The gas to gas separation either works at high pressure or low pressure.

Cryogenic separation is based on the fact that carbon dioxide can be separated from biogas as a liquid by cooling the gas mixture at elevated pressure. Methane has a boiling point of

– 160 ^{o}C whereas carbon dioxide has a boiling point of – 78 ^{o}C.

In in-situ methane enrichment carbon dioxide that is dissolved in the sludge from the digestion chamber is desorbed in a column where it meets a counter flow of air.

The cryogenic method has only been tested in pilots plants in Europe while the in-situ technology still is on a laboratory scale.

Cleaning

Hydrogen sulphide can be removed by biological desulphurisation, Iron chloride dosing to digester slurry, conversion by impregnated activated carbon, by reaction with iron hydroxide or oxide or by scrubbing with hydroxide.

Halogenated hydrocarbons are predominantly found in landfill gas and can be removed with the same methods used to remove carbon dioxide.

Siloxanes (organic silicon compounds in biogas can be separated by help of activated carbon or through cooling the gas and separating the condensed liquid.

Oxygen and/or nitrogen present in the gas signs that air has been sucked into the system. This is common in landfill gas and high levels of oxygen can pose a risk of explosion. Oxygen and nitrogen are to some extent removed by PSA.

The biogas is saturated with water when it leaves the digestion chamber. This water has to be removed before it is used as a vehicle fuel or fed into a gas grid. Refrigeration or adsorption of water on the surface of a drying agent are a common methods for drying biogas.

Finally the report gives some short data on costs for upgrading and also describes case studies in:

- Hardenberg, The Netherlands (grid injection)
- Kristianstad, Sweden (manure and waste digestion)
- Stockholm, Henriksdalö and Bromma, Sweden (sewage sludge)
- Lille, Marrquette, France (sewage sludge)
- Jona Switzerland, (grid injection)

There are also a list of 31 selected reference plants by 2006 in Austria, Canada, France (2), Germany (5), Iceland, Japan (2), The Netherlands (4), Norway, Spain (2), Sweden (15), Switzerland (7) and The USA (10).

Part 2

In present report, in first hand technical, but also economical, facts and experiences from biogas upgrading in the European biogas plants in Lille, Stockholm and Rome are described. Concerning Bern and Gothenburg the plants are not yet operational (demonstration might be possible during 2007) while the information about them in the report focus mainly on the planning and erecting phases.

The authors anticipate that this information can be used by new interested parties who consider the possibility to start producing and/or upgrading biogas to vehicle quality. The intention is to help new parties to somewhat avoid repeating "old" mistakes and to learn from established solutions and the knowledge gained in this project.

Some of the main conclusions that can be drawn from the reporting from the sites mentioned above are:

- The technologies used by the WP 3 sites, pressure swing absorption, water scrubbing and chemical absorption all have prons and cons but still are from a overarching perspective more or less equivalent in efficiency, gas quality, energy consumption etc.
- These technologies as well as used cleaning technologies have today reached a level of maturity when they can be described as established technologies available at the open market and the buyer can expect installation and operation to be carried out without any severe problems. However, when installing and starting up equipment for gas upgrading it is important to keep in mind that every plant is unique and the equipment in more or less all cases need time for adaptation and adjustment before full production capacity can be reach
- Upgrading of landfill gas tends to be somewhat more difficult than upgrading gas from a controlled plant for anaerobic digestion of a specific feedstock/biomass.. One reason to this is probably that landfill gas often contains more contaminants, such as for example hydrogen sulphide and halogenated hydrocarbons, than gas from a well controlled plant with a more homogeneous feedstock. Because of this an upgrading facility for landfill gas might have to be somewhat more sophisticated and with a higher total efficiency which might be reach by combining different upgrading and cleaning technologies.
- When upgrading and using landfill gas it is important to take into account that the raw gas quality also will differ over the seasons related to seasonal variation of the waste disposed at the landfill.
- It is important to have a back up system for the gas production so that operational problems resulting in for example low production capacity and/or insufficient gas quality (out of specification) can be solved. For example a production/upgrading plant can have an agreement with another plant to support each other and to deliver gas to each other in case of gas related problems. It is also recommend to have two smaller parallel production lines (instead of one big one)to be able to at least stick to the half production capacity if one line runs into problems.
- At least during the start up period it is important to collect and save as much operational data as possible since this will make it easier to obtain and understand the real issues behind a production related problem.
- Concerning new upgrading technologies there are still a lack of data from operation. However, the cryogenic separation technology seems to have advantages that might make it a possible second generation upgrading technology.
- The introduction of biogas as a vehicle fuel would certainly be facilitated if there was a national or rather European (CEN) biogas standard. Such a work on a European level has to be carried out by The European Standardisation Organisation, CEN. As a starting point for such a work the Swedish national biogas standard, SS 155438 “Biogas as fuel for high speed otto engines”, could be used. One result of Biogasmax project could be a request from the project or an mandate from EU to CEN to start up a work on such an European biogas standard for vehicle use.

Based on the reporting from the involved sites it is also possible to highlight a number of positive experiences such as:

- The use of biogas results in lower emissions to air of harmful emissions and when used in city centres it can contribute to improved the air quality.
- The cost for operation and maintenance decreases when the vehicle operator over time gains knowledge and experiences.

- The higher investment cost of a biogas vehicle, compared to a diesel fuelled vehicle, is well compensated, over the life time of the vehicle, by today lower biogas price compared to the price of diesel oil.
- Drivers as well as people in common are to a high extent positive to the use of biogas
- Vehicles running on biogas (methane) have compared to diesel oil fuelled once lower noise levels – lower sound emissions

However, there are also some negative experiences that have to be mentioned:

- The production of raw biogas is a "living" biological anaerobic fermentation process which makes it sensitive for changes in for example feedstock supply (quantity and quality (including unwanted toxic substances)), whether conditions (cold, warm climate) etc.
- Even low concentrations of emissions such as hydrogen sulphite and halogenated hydrocarbons will result in piping attrition which makes it more or less necessary to use stainless steel in all constructions and as far as possible to keep the gas over the dewpoint at the actual pressure
- Limited operational range of the vehicles
- Engine problems related to variations in the biogas quality (out of specification).

Furthermore one important result from the work in WP 3 is a list of recommendations set up by the participants in BIOGASMAX WP 3. A list that might help new interested parties to avoid some obstacles during their way from planning to production. The recommendations are presented without any prioritisation.

1. It is necessary to obtain exact figures for (i.e. quantitatively) the potential for biogas production (and the feedstock).
2. It is also necessary to be aware that the technologies used often needs adjustment periods..
3. Do not hesitate to over proportion the infrastructures to be sure that the objectives can be reached (considering biogas quality).
4. Ask the infrastructure builder for some kind of results guarantee.
5. Pay attention to the climate impact on exterior infrastructures.
6. Try to take into account the knowledge gained by someone who has built and operated a plant similar to the one that is planned.
7. Be exact and detailed in your tender specification documents.
8. Put up a demand in your tender document concerning the dryness of the gas

Annexed to this part of the report are also three matrices in which the commonly used upgrading technology today, as well as "new" probably coming technologies are compared to each other in general and from a technical point of view, as well as from an economical point of view.

Part 1

Biogas Upgrading and Utilisation

This is Part 2 of the report and is available separately, as pdf and quality print version.

Part 2

Biogas upgrading - Facts and Experiences from Stockholm (SE), Gothenburg (SE), Lille (FR), Bern, (SW) and Rome (IT

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1. Background and Introduction

1.1. Background

The overall goal of the BIOGASMAX project is to support the European Community in reducing its dependency on fossil oil resources, reducing greenhouse gases and direct emissions through knowledge about production that is more efficient, distribution and use of biogas in the transport sector generated from a wide variety of feedstock available in urban regions in Europe.

During its 4-year life cycle, BIOGAMAX has had the aims to:

- Prove the technical reliability, cost-effectiveness, environmental and social benefits of biogas as a fuel.
- Perform large-scale demonstrations to optimise industrial processes; conduct experiments on these processes; benchmark new and near to market technologies and to expand the biogas fleets.
- Identify and assess ways to remove technical, operational, organisational/institutional barriers, which can be inhibit or prevent alternative motor fuels and energy efficient vehicles from entering market.
- Spread knowledge about experiences and results to European cities and stakeholders with emphasis on New Member States (NMS) to enhance the market acceptance of biogas as an alternative motor fuel.

Demonstrations are undertaken among the partners in Lille (FR),, Stockholm (SE) and Rome (IT) whileBern (SW) and Gothenburg soon will start up and demonstrate their facilities. (

The work in BIOGASMAX is carried out in different work-pages.

Work-Page 3 (WP 3) covers the upgrading process and system.

The overall objectives of WP 3 are:

- Optimum technical applicability of biogas upgrading technologies
- Economic profitability of biogas upgrading technologies
- Minimum secondary waste generation and energy consumption
- Optimum fuel yield

This report is one of the results of the work in BIOGASMAX WP 3

1.2. Introduction

Biogas is a product from anaerobic digestion and the gas composition is primary comprising methane (CH_4), carbon dioxide (CO_2) and small amounts of water and impurities.

Biogas (raw gas) can be used for heating and cooking as well as in combined heat and power production plants.

For some applications the quality of the gas has to be improved – CO_2 has to be removed to increase the energy content in the gas up to, or close to, the natural gas standard. Often a methane content of more than 96 - 97 % is required. This process is normally designated as “upgrading”.

Furthermore, water and other impurities such as Hydrogen sulphide (H_2S) and halogenated compounds have to be removed since they might have a severe impact on materials through corrosion. They are also toxic to man. This process is normally designated as “cleaning”.

These both processes can be handled in separate process steps but they can also be managed at the same time in a joint process.

Today, the most commonly used technologies for upgrading, with or without cleaning, are absorption with water or chemicals (scrubbing of the gas) or so called pressure swing adsorption (PSA) with adsorption on activated carbon.

New technologies are, for example, cryogenic upgrading, molecular sieves and separation membranes..

In this report, the work on upgrading and cleaning including some technical and economical data concerning the plants in Lille, Stockholm and Rome are described together with a summary of experiences gained at these plants. Furthermore are the planned (or under construction) plants in Bern and Gothenburg described from a technical point of view.

The experiences and results described in the report are based on information that has been provided by the plant staff as a response to a survey sent out in June 2006, as a part of the work in BIOGASMAX WP 3.

The objective behind the survey and the report was to make valuable information publicly available. Thus, new intrested parties, who might start up biogas plants or biogas upgrading facilities, can use this information for their planning instead of “inventing the wheel one more time”.

2. Studied biogas plants including upgrading facilities

2.1 Lille

The Marquette sewage plant in Lille, France, was built in three stages. The first stage was put in operation in 1969 and it then already included digestion and biogas recovery through cogeneration (electricity and heat production). Thus, the equipment used at this plant date from the initial phase of operation of that plant.

Picture 1. The Marquette sewage treatment plant

The plant was built to treat 750 000 EqH (number of normalized people connected to the plant) but the sewage water actually received is equal to about 450 000 EqH. The plan treats about 120 000 m^3 used water/day. This plant is the only sewage plant in the Urban Community of Lille using a sludge digestion system to reduce their quantity of sludge rest and to produce biogas.

Between 1975 and 1977, two additional stages for water treatment were built. To increase the water treatment efficiency of the plant, the sewage plant was further amended to improve the water treatment efficiency, which indirectly led to a raw biogas having a lower content of H_2S.

The sewagesludge was digested in four digesters, two primary digesters (6 000 m^3 each) and two secondary digesters (3 000 m^3 each).

The raw biogas produced had the following characteristics:

CH_4 63,5%
CO_2 35,5%
N_2 0,7%
O_2 0,2%
H_2S 3 000 ppm

In 1990, the decision was taken to launch the operation designated ”Methane fuel operation”.

Between 1993 and 1995, a pilot plant, to upgrade raw biogas to fuel quality biogas, was built. It utilised water-scrubbing technology and was sized to refuel four buses from the municipal fleet. The Marquette biogas fuel-production unit started to be operational in April 1995, but its devising lasted two years (1995-1997)

Analysis performed on the biogas fuel produced in Marquette showed that it was of a very good quality:

- The concentration of corroding agents (H_2S, total sulphur, H_2O) was very low. The H_2S elimination rate was above 99 %, and the H_2S concentration in the biogas produced in Marquette was substantially below the specification limit of 5 ppm (part per million). On average, the H_2S concentration was about 2 ppm, while the H_2O concentration was about 3 ppm.
- No emissions of non-methane hydrocarbon (NMHC) were detected.
- The calorific value of the biogas produced was better than the H gas standard (higher than 10,7 kWh/Nm^3 (Normal cubic meter), where the H gas limit corresponds to a methane concentration of 96,7 %). This result was due to an average content of 97,5 % methane, which can reach 99 % at maximum. This data were due to a high CO_2 elimination rate (95-99 %); the CO_2 content was, on average, 1,6 %.
- The density was low, but the Wobbe index was high.

About 80 Nm^3 per day of upgraded biogas (97,5 % methane content) was produced and intended for the refuelling of four buses.

The plant was more or less operational at all the time. For instance, an average day of use (7-hour day) was constituted by:

-3,2 Hours of valid gas production

-1,3 Hour of “start-up”

-0,4 Hour of tests

-2,1 Hours of no operation

In May 1997, this average improved due to the gradually increasing reliability of the gas treatment unit:

-4,9 Hours of valid gas production

-1,5 Hour of ‘start-up”

-0,1 Hour of tests

-0,6 Hour of no operation

After 9 years of running, the decision was taken in 2004 to stop the pilot plant since it had several safety-related problems due to attrition (corrosion of several parts of the equipment). Moreover, the pressurised storage vessels for upgraded biogas had to be replaced since they had reached their useful life limit.

Due to the problems mentioned above, it was also decided in 2004 to replace the pilot plant by a reliable industrial installation. This facility was equipped with the technological developments that were implemented in Sweden, see description below, during this period. The choice for this new infrastructure builder wasmade during the summer of 2006. The plant capacity will be slightly increased. The original principle of cogeneration will remain. Most of the biogas produced by the plant will still be used for electricity and heat production.

For the future gas infrastructure, raw biogas consumption will be 1 100 Nm3/day (vs. 80 Nm3/day previously) and upgraded biogas production will be 1 320 Nm3/day (vs. 35 Nm3/day previously). The NGV (Natural Gas Vehicle) gas storage will be oversized at 4 m3 (i.e. for 10 buses).

2.2 Stockholm

2.2.1 Bromma

The Bromma Sewage treatment plant produces biogas (raw gas) from the anaerobic digestion of municipal sewage sludge.

The Bromma sewage treatment plant is designed to treat sewage water from 260 000 inhabitants.

The numbers of digesters are six, having a total volume of 12 000 m^3 and presently, 20 days of digestion time. The feedstock in 2005 was 0,14 M (Million) ton of primary sludge and 0,07 Mton of secondary sludge (WAS).

Initially, the raw gas was used for heating in the internal processes. Since the previous volume of raw gas production was more than the amount required for heat consumption, large quantities of biogas were flared at that time.

In 1995, a discussion started about how to utilise the surplus energy. Finally, this resulted in the procurement of a demonstration water-scrubber pilot plant in 1996.

The plant included the following main components:

- Two water scrubber skids of 55 Nm^3/h each of raw gas capacity,
- A 1 900 Nm^3 high-pressure fuel storage
- One dual hose 3 line fuel dispenser

With the following data:

- Time of operation: 1996-2000
- CBG (Compressed Biogas)/year: 0,36 Mm^3/ year
- Flow - untreated gas: 55 m^3/ h (per production line)
- Flow - treated gas: 25 m^3/ h (per production line)
- Water flow through scrubber: 120 litre/min (per production line)
- Untreated gas quality: ca 65 % CH_4, ca 35 % CO_2 + N_2, H_2S, water vapour
- Treated gas quality: ca 97 % CH_4, ca 2 % CO_2, 1 % N_2
- Compressor pressure: up to 250 bar
- High-pressure storage: 1900 Nm^3

The scrubber technology had a closed water circuit with no methane release to the atmosphere. The process had a continuous water supply where the process water was returned back to the common gasholder in which the absorbed carbon dioxide and residual methane was released. The system design was unique and possible to use, hence the gas treatment process only used a smaller portion of the produced raw gas. The size of the pilot plant was also the smallest units ever built with a 4-stage compressor used for compression of both the raw gas and the CBG.

The plant pilot was replaced and scrapped in 2000 due to high production costs, insufficient capacity to meet the demands and lack of reliability.

Two new gas treatment lines with a total capacity of 600 Nm^3/h was installed in 1999 based on a PSA (Pressure Swing adsorption) with beds of active carbon and with the following technical data:

- CBG/year: 2 x 1,5 Mm^3/ year
- Planned flow - untreated gas: 130 - 260 m^3/ h (per production line)
- Planned flow - treated gas: 85 - 170 m^3/ h (per production line)
- Untreated gas quality: ca 65 % CH_4, ca 35 % CO_2 + N_2, H_2S, water vapour
- Planned treated gas quality: ca 97 % CH_4, ca 2 % CO_2, 1 % N_2
- Compressors pressure: Up to 260 bar
- High-pressure storage: The same storage is used as for the pilot plant

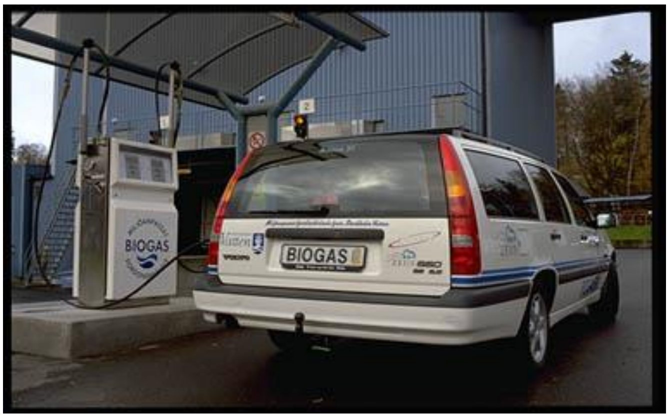
The PSA plant is presently still in continuous operation. Previous experiences were implemented in detail and the availability of the present production lines is very high, i.e. above 99 %. It also produces biogas having a very stable quality. The lines have full redundancy and can be operated separately or jointly to guarantee at least half production capacity even during service and operational problems etc.

The gas from the raw biogas storage is first separated from water by condensation to a specified dew point (< -30 ^{o} C at 250 bar, but whenever possible <-35°C at 260 bar). The pressure of the gas is increased up to 5 bars and H_2S is separated in the pre-filter of the PSA equipment. In the PSA, carbon dioxide is removed and the biogas is dried in a gas cooler thereafter. The PSA plant has four separate synchronised absorption reactors that work in a cyclic mode changing between low pressure, pressure balancing, gas cleaning and gas blowing.

Finally, the gas is compressed to a pressure of 260 bar and is transferred to a vehicle gas storage having a total capacity of 5 000 Nm^3.

Furthermore, a new public dispenser outside the fence, which is easily accessible for external consumers, has been erected. In addition, Bromma has a complete refuelling system for gas containers intended for distribution of biogas to isolated refuelling stations.

Picture 2. CBG filling the first biogas vehicle at the pilot plant



Today, more or less all biogas produced in Bromma is upgraded and used as a vehicle fuel.

The pilot plant had a long row of failures based on unsuitable components, materials, setting of parameters and insufficient capacity. Several parts of the process had to be redesigned and the combined duty for the compressor with dirty and wet gas combined with high pressure made the system too complex. Generally, the pilot plant needed continuous attention whilst the second plant is mostly handled by remote access.

In contrary to the first plant, the second plant has proved the opposite in reliability and has been in operation since start without any major failures. Few items were re-designed as a result of the final performance tests.

2.2.2 Henriksdal

The Henriksdal sewage treatment plant processes sewage water from the inner and southern parts of Stockholm. The sewage treatment plant produces about 9 million Nm^3 of raw biogas by anaerobic digestion of the sewage sludge from cleaning of sewage water.

In 2001, a biogas upgrading plant was constructed and erected at the Henriksdal Sewage plant. The upgraded gas (compressed biogas, CBG) is used as a motor fuel but also for cooking and heating in a housing area with predominantly apartment blocks close to the sewage plant, Hammarby Sjöstad.

- Feedstock: 0,56 Mton primary sludge and 0,16 Mton secondary sludge (WAS) (2005)
- Time of operation: 2002/2006 – both lines still in operation
- CBG/year: 8 Mm^3/ year
- Flow - untreated gas: 600 and 800 Nm^3/h (per production line)
- Flow - treated gas: 400 and 500 Nm^3/ h (per production line)
- Water flow through scrubber: 90-120 m^3 / h (closed loop)
- Untreated gas quality: ca 65 % CH_4, ca 35 % CO_2 + N_2, H_2S, water vapour
- Treated gas quality: ca 97 % CH_4, ca 2 % CO_2, 1 % N_2
- Compressors: up to 350 bar
- High-pressure storage: 7 000 Nm_3
- LNG Liquefied Natural Gas) storage 66 000 Nm^3

The upgrading plant was built in two phases. Presently, the total capacity of the two lines is 1 400 Nm^3/h, which gives a possibility to produce around 6 million Nm^3 of CBG per year.

Both lines are based on water scrubber system and one line has an additional 350 bar compressor for the local HP (high pressure) storage. The water scrubbing system uses recirculated water where carbon dioxide and H_2S is absorbed in water. After the scrubbing/cleaning process, the water is cooled and re-circulated while the carbon dioxide and the H_2S are vented out through the ventilation system and chimney of the sewage plant. Finally, an odour additive is also being added to the cleaned gas to make it possible to detect leaks.

The Henriksdal plant supplies a bus depot with biogas through a 4-bar pipeline. The tunnel for the 4-bar pipeline has been drilled through the Henriksdal bare hillock, under the Hammarby canal and it finally ends at the South bus depot.

The CBG pressure is then to 350 bar working pressure at the bus depot for the 3 bank high pressure CBG storage, which quick-fills all buses through three dual hose dispensers with temperature compensated filling pressure.

All dispensers are installed in parallel and have their own individual control as to choose which bank will be utilised during the filling process to optimise the CBG storage and reduce the filling time. Each bus is a new condition for the filling process depending on the total volume of the bus cylinders and remaining CBG in the bus to estimate the refill volume. The total storage capacity is 7 000 Nm^3.

Picture 3. Henriksdal gas treatment plant

Picture 4. Bus depot with three compressors and 350 bar CBG storage

The availability of the CBG is so crucial that a LNG storage with vaporiser as a back up has been installed. The capacity of this storage is 66 000 Nm^3.

The plant has showed good reliability and it has been in operation since start without any major failures. Few items had to be redesigned as a result of the final performance tests.

2.3 Rome

AMA started its experience in biogas-fuelled captive fleets in January 1995. This work was carried out in collaboration with IVECO and CO.LA.RI, the private consortium that owns and operates the Rome landfill (Malagrotta). Malagrotta is one of the biggest sanitary landfills actually in operation in Europe (more than 1,5 million tons/year disposed and/or treated). However, AMA is not operating that landfill.

The biogas production from the landfill is great enough to generate electric energy and biogas for the refuelling of about 34 public and private vehicles. Biogas is continually tapped and extracted out from the 660 wells drilled on the landfill site.

The electric energy generated is delivered from two plants capable of generating 15 MW of electric power. Electricity generation is made in 2 turbines and 6 motor generators,

The first experiments on the use of biogas (upgraded landfill biogas) in vehicles started in 1995. The upgrading plant was built before that, i.e. it was completed in 1994. The decision to build an upgrading plant was probably the huge amount of natural biogas produced by the anaerobic decomposition of the organic matter that occurs inside the sanitary landfill.

In 1998, the raw methane production was about 900-1 000 Nm^3/h and the production of the upgraded biogas was about 400 Nm^3/h, which is equal to 9 600 Nm^3/day.

Considering an average operation of 1,2 km per Nm^3 of biogas, this means that a total driving distance of 10 600 km/day can be covered by the biogas-fuelled vehicles.

From the official documents, the minimum expected figures for biogas by sanitary landfill are:

Biogas total production:	130 Nm^3 / ton $_{MSW}$
Biogas extraction efficiency	0,85
Biogas yearly extraction capacity	6,7 Nm^3 / year and ton $_{MSW}$ (calculated on 15 years)

Average composition of raw biogas (figures year 1998):

Component	**(in volume)**
CH_4	50-60 %
CO_2	37-47 %
H_2S	0,5-1 %
N_2, O_2, H_2	from 0 to 3,5 %
H_2O	saturated
HCLl, HF, Si	5- 10 ppm (vol)
Energy content (lower)	17 850 kJ/Nm^3 (4 263 400 $kCal/Nm^{3)}$

Raw biogas from the wells is first pre-filtrated from solid particles and also separated from water by condensation followed by H_2S separation in 2 desulfuration towers containing iron oxides. Iron oxides is chosed instead of for example activated carbon since the regeneration is cheaper and more efficient.

In a second step the pressure of the gas is increased up to 9 bars by low and medium pressure compressors, and due to refrigeration separated from water and oil, followed by water scrubbing where the carbon dioxide is absorbed from the gas The carbon dioxide is further removed from the scrubber water in a stripping tower and the water is re-circulated .

Upgraded biogas specification after water scrubbing:

Component	**(in volume)**
CH_4	90 %
CO_2	10 %
H_2S	1-5 ppm
N_2, O_2, H_2	no variation
H_2O	Saturated

In a third step the gas, after separation from water drops, but still saturated, goes to a pressure swing absorption (PSA) unit where further CO_2 and humidity is separated from the gas by absorption on zeolites

Upgraded biogas specification after PSA

Component	**(in volume)**
CH_4	97-99 %
CO_2	1-3 %
H_2S	1-10 ppm
N_2, O_2, H_2	no variation
H_2O	1-3 ppm
HCL, HF, SI	<= 1 ppm (vol)

The upgraded and dried gas is obtained at intermediate pressure of 7-8 bar, is compressed up to 220 bar and stored in 6 tank groups having a total capacity of 18 000 Nm^3 which is sufficient for an operation of 4-5 days

Gas that doesn`t meet quality specifications and the process gas is re-cirkulated .

The plant is delivering biogas to a fuel station, which has 8 fuel pumps that are able to operate at the same time. There are also booster compressors to allow high speed fuelling.

Picture 5. AMA Biomethane waste trucks at Malagrotta biogas filling station

From 1995, the upgrading plant has been operated continuously, except for scheduled maintenance work, and it is still in operation.

For the moment, AMA is tendering the construction of an anaerobic digestion plant, which will produce approximately about 10 MNm^3 / year of raw biogas. AMA is going to study the feasibility for the use of this upgraded bioga in captive fleets. The results of this study will be submitted as soon as it will be ready..

2.4 Bern

2004 in Bern discussions started about replacing diesel fuelled buses by gas fuelled once. Since one important key element in all discussions was the reduction of green house gas together with the reduction of other emissions such as for example particles biogas was one interesting alternative that was analysed.

The Main source for the biogas production will be digestion of sewage sludge from wastewater treatment. However, the biogas will not be used directly after upgrading, instead it will be injected into the local natural gas grid. Therefore, the gas buses will use a mixture of natural gas and biogas (physically approx. 1% biogas).

During 2005 it became possible to set-up letters of intent, and after having sorted out the financial questions, corresponding contracts could be signed in the beginning of 2006.

Thereafter the planning of the upgrading system and the connecting pipe for the gas injection into the natural gas grid was done quickly. Today the pipe is built, and everything else is ready except the up-grading system itself. However, an upgrading system from CarboTech Engineering GmbH is ordered and will be delivered this summer, planned to be operational not later than October 2007.

The technology used will be pressure swing adsorption (PSA) with a raw gas capacity of approximately 300 Nm^3 per hour. After upgrading the maximum capacity will be approximately 192 Nm^3 per hour of upgraded biogas with a pressure of 5,5 bar and a specification of:

CH_4	> 96 %
CO_2	< 6 %
H_2S	< 5 mg/m^3

Additional feedstock for digestion to biogas is planned to be used when the up-grading system becomes operational, i.e. gastro waste as well as fat from the milk industry.

With the planned certification system BERNMOBIL will receive approx. 13 MWh/annum biogas (later more) which is good for the operation of 30 buses.

<u>So far no problems have been experienced. However, there has not been any operation/production carried out yet.</u>

2.5 Gothenburg

In Gothenburgh the local Energy Company, Göteborg Energi has bought the biogas produced from digestion of sewage sludge by the local water cleaning company since year 2000.

Until today the biogas has been used in gas engines and also been injected into the city gas grid. The city gas grid has contained a mixture of natural gas and air. However, using biogas in a gas engines demands a lot of maintenance of the engines because of the variations in the methane continence, which results in to high costs. The biogas shall for the future only be injected in the natural gas grid. Since the city gas grid it is going to be converted to pure natural gas in Gothenburg the biogas has to be upgraded and also added with some propane..

2004-03-02 decission was taken to start the project to build and operate an upgrading facility, 2005-09-08 decission was taken to start building the upgrading facility and in March 2007 final inspection and take over from the construction company is planned. Yet the plant is only tested but not operated with max capacity. However, from the test results it looks like the upgraded gas will fulfil the requirements in the biogas specification.

The upgrading technology used is a form of chemical absorption called “Low pressure - CO_2 absorption” based on low pressure reversible chemical absorption, specifically designed to remove CO_2 from biogas. The absorption liquid is an amine composition.

In a first stage the raw gas is filtrated by active coal to remove H_2S.

In a second stage the raw gas meets the amine liquid in a scrubber tower and CO2 reacts with the amine.

The upgraded biogas is then dried and added with some propane before it is added to the natural gas grid..

The amine liquid finally has to be boiled to release the CO_2 to the atmosphere before it is re-cirkulated to the scrubber tower.

The gas capacity of the plant will be 1600 Nm^3/h raw biogas and approximately 1100 Nm^3/h upgraded gas.

Average raw gas specification:

CH4	65%,
CO2	34,4 %,
H2S	max 10 ppm,
O2	<0,1 %,
N2	< 0,5 %

Upgraded biogas specification:

CH_4	> 96 vol %
CO_2	< 0,5 vol %
0_2+N_2	< 4 vol %
Dew point	- 60 ^{o} C at 4 bar g

After adding of propane 95:

Heating value lower 11,1 kWh/Nm^3

3. Upgrading of biogas – Experiences and Obstacles

Biogas quality problems

The main problem encountered in the Lille project was the difficulty, from the beginning of the pilot to the end of its exploitation, to obtain a biogas fuel that conformed to the planned specifications. Rome had at least initially a similar problem concerning the gas quality and to obtain according to the planned specification

In Stockholm, oil in the gas has been a problem from time to time, especially at filling stations using hydraulic compressors.

Next to this, water in the CBG has been the most significant quality issue. In first hand, most experiences from Stockholm relates to contaminations, such as water and oil but also in some cases even desiccant dust from the molecular sieve dryers.

Solution

To improve the gas quality in Lille, a system had to be introduced to re-circulate the gas that did not correspond to standard, in order to upgrade it again. At the beginning of the operation of the pilot, the gas had to be re-circulated several times.
Rome has also used a system for re-cirkulation when the gas did not meet quality specification. However, it was also concluded in Rome that one important problem to meet the specification over the year was connected to the seasonal variations in the dumped waste, which influenced the possibility to over time keep a constant quality (specification) of the biogas.

As a tool to guarantee the gas quality in Stockholm, a CBG standard was established. This standard helped the participants in their work to focus on the same target. This specification (a Swedish standard today SS 155438) stated inter alia the quantity of impurities allowed in the CBG such as H_2S, water, oil, inert gases etc.

Concerning water contamination, the permitted water content of the gas in Stockholm was previously set to a defined dew point of at least -30°C at a pressure of 250 bar but when possible –35 ^{o} C at a pressure of 260 bar,This limit was only based on practical experiences rather then any scientific evaluation. The problems with ice blocking of valves during the vehicle refuelling process simply disappeared at this moisture level.

General recommendations

A well controlled biogas quality in line with a defined vehicle biogas specification/standard is strongly recomended, to avoid enginge performance and emission problems. This requires a well functioning and operated upgrading facility as well as a frequent follow up of the biogas specification/standard parameters in combination with modern precise instrumentation of the upgrading facility.

Gas quality problems can to some extent be solved by temporary solutions such as re-cirkulation of the gas but if the problems continues for a longer period the technical solutions have to be taken into consideration to decide if to replace older parts of the upgrading plant with new modern ones adjusted to the quality requirements of the biogas.

When dealing with landfill gas, quality problems might be an effect of seasonal variations in the dumped waste. This problems must be solved in co-operation with the dump owner/manager in such a way that the variations in waste dumping over the year not influence the raw gas quality.

When replacing old parts or when building a compleately new upgrading facility it is important to be exact and detailed in the tender specification documents, not at least concerning capacity, impurities in the gas - demand on the choice of materials, as well demand on the equipment.

Equipment problems

Many operational problems also occurred at the plant in Lille. The basic cause was, in first hand, the fact that the pilot plant was not thoroughly implemented. Neither was it fully equipped with transducers, sensors and flow meters for pressure, temperature, and water flow. This problem was to a great extent linked to the fact that lots of parts in the plant were not made of stainless steel, which led to wall and piping attrition, because the raw biogas was highly contaminated by H_2S *– i.e. 3 000 ppm.*

Another problem was the incompatibility between the compressor (devised for compressed air) and the gas properties.

Similar problems as in Lille also occurred in Stockholm. Furthermore, the Bromma project was heavily delayed since the supplier of equipment to Bromma had a severe delay in supplying unfinished equipment to site. In addition, all the technology used was new so there was simply no experience to rely on and a lot of the work was carried out on a trial and error basis.

The problems and solutions involved everything from redesign, change of components to substitution of materials. Most problems related to design errors, insufficient organisation and lack of competence from equipment suppliers.

Except for the start-up phase of a new plants, with humidity in the pipes etc., malfunction of the gas dryers have been the most critical problem to overcome.

Rapid pressure drops and gas flows upwards (popcorn effect) turned the desiccant in the molecular sieves into dust. In sufficient regeneration cycles, leaking valves and uncontrolled heating processes was the main reason for saturated drying beds with insufficient and unreliable function as a result.

Solutions

The way to overcome the initial problems in Stockholm was to learn more about how the gas processes behaved. There were no previous experiences, neither to rely on nor to utilise. To overcome that problem, a systematic program had to be initiated. In first hand, all possible data had to be collected to gain more knowledge about the processes. It was quickly realised that a process disturbance was often linked to a previous cause, which in many cases not could be seen at the time of the stop.

The collection of data showed that it was necessary to upgrade the level of instrumentation and store all operational data. This data bank proved to be invaluable in all problem-finding work. By identifying the probable errors rapidly, it was possible to quickly establish an action plan and consequently, to improve the process of problem solving.

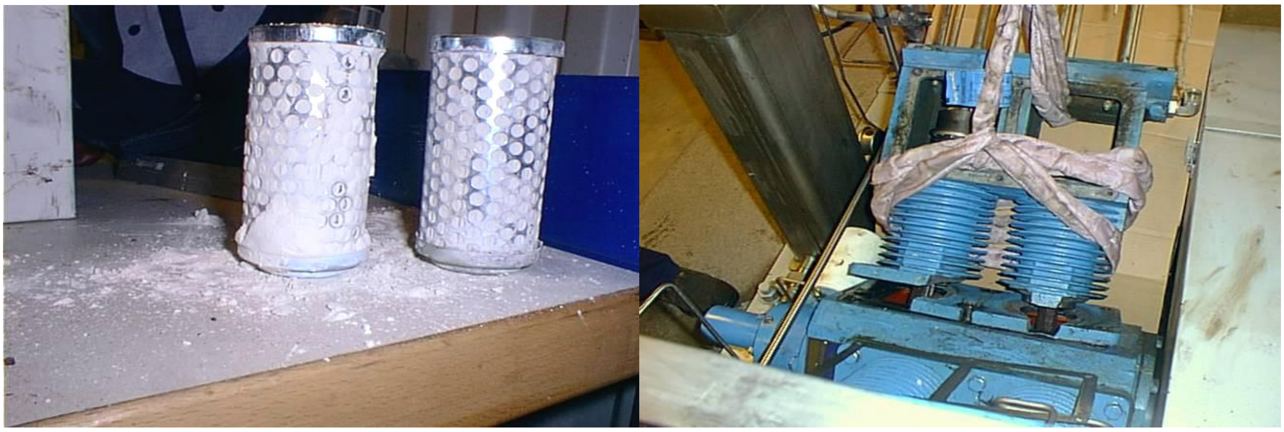
The first pilot plant also required a lot of attention such as hands-on adjustments, problems finding etc. These efforts lead to that this was the highest single operational cost of the plant.

Furthermore, all experiences gained over time were collected and implemented in every new tender document for new plants. The process knowledge and technical requirements were improved for every new project, which raised the awareness and competence of the contractors.

Today, several gas treatment solutions have been developed that correspond to a high standard and very high availability. This has reduced the production cost considerably. The operation and maintenance costs have dropped and they are now nearly at the same level as the cost of the energy consumed.

Concerning gas dryers, new dryer design has resulted in change of sequence, better control system and new components that have contributed to resolve the situation.

Picture 6. Pilot plant CBG problems with desiccant from dryers and a broken compressor due to water in the gas



General recommendations

Concerning technical equipment it is important to chose materials and technical solutions that are adapted to the real situation concerning gas flow, raw gas quality (impurities) etc and that withoutant severe problems can resist attrition such as corrosion from impurities in the gas. It is also important to carry out the process at a temperature and pressure (-30 o C at 250 bar) that not allows any rests of humidity in the gas to condense on pipe walls or inside technical equipment, with risk of corrosion as well as building up of ice in pipes and for example compressors.

When starting up or when having problems in a running upgrading facility it is important to not only collect but also save collected data to make it possible to go back and look for the, so to speak, background of the disturbance. The problem for the moment is often is linked to a previous cause, which in many cases not could be seen at the time when the problems occour.

To be able to collect and store data in such a way that previous causes can be detected it might in already perating facilities (primarily older once) be necessary to upgrade the level of instrumentation.

However, when talking about problems in new facilities it is also important to take into account that new facilities always need some time for starting up as well as adaptation of the process before full production capacity (quality and quantity) can be expected

4. Distribution and use – Experiences and Obstacles

In Lille, the upgraded biogas was used in one or two buses.

Two main problems occurred during the use were:

- First, due to logistic problems, the pilot plant was not used up to its full capacity. The plant was configured for fuelling six buses per day, but only one or two buses were refuelled per day. That was due to a quality difference between the upgraded biogas and natural gas. In France, there are two types of gas - H gas (which corresponds to the gas quality distributed in the south of France, having an energy content similar to Swedish upgraded biogas), and B gas (for the north of France, i.e. gas coming from the Netherlands). Since biogas was corresponding to the H gas quality and natural gas was equal to B gas quality, a bus had to wait until its natural gas tank was empty to refuel it with biogas. Mixing was impossible due to the difference in energy content. The under-utilization of the pilot plant also generated maintenance problems due to the under-utilization itself.
- Secondly, there was no bus depot close to the pilot plant. The nearest bus depot was 10 km away. Consequently, the buses could not be parked where they were refuelled. The driver could not refuel by him or herself. Moreover, the access to the plant was very inconvenient for the buses (one-way-street).

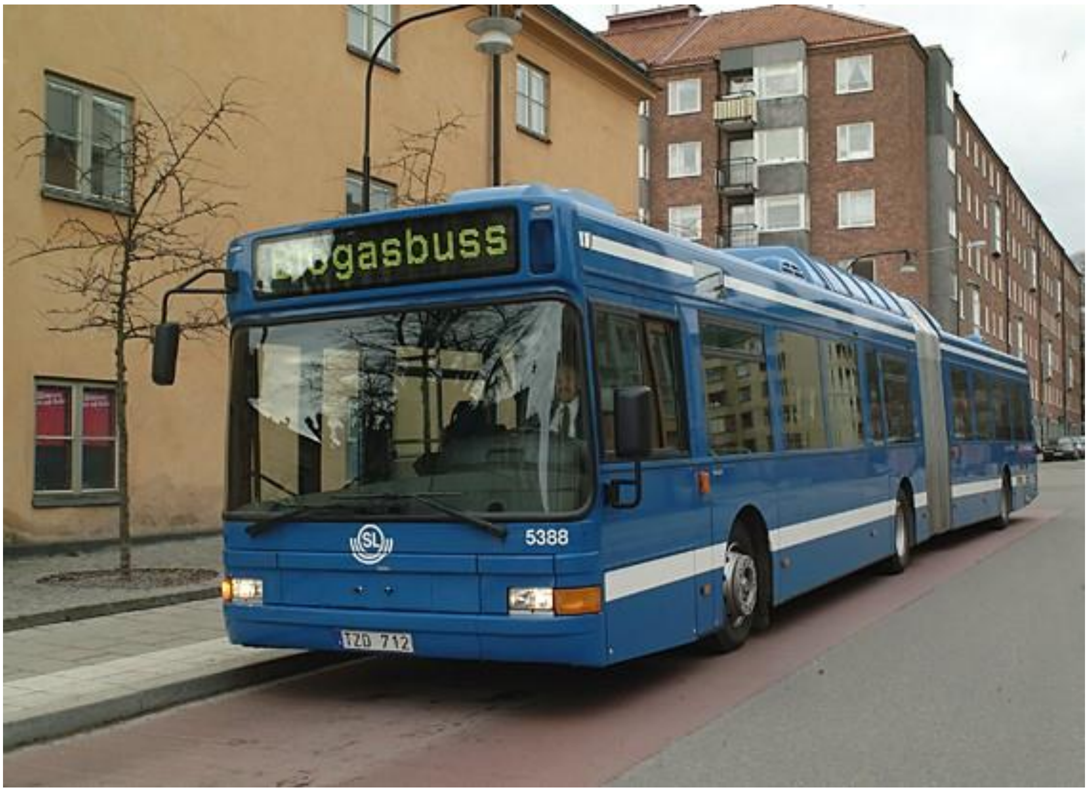
Picture 7. Refuelling a biogas bus

The gas from the Marquette plant was distributed at the sewage plant itself, thanks to a refuelling station that provided a high-pressure surge tank (using 24 50-l bottles).

Picture 8. Biogas fuel storage unit at Marquette

In Sweden, the largest CBG consumers of all biogas vehicles have been, and still are, the bus fleets. The number of CBG buses has increased over the years and is still increasing. Some other cities in Sweden have now converted practically their whole bus fleets to CBG operation.

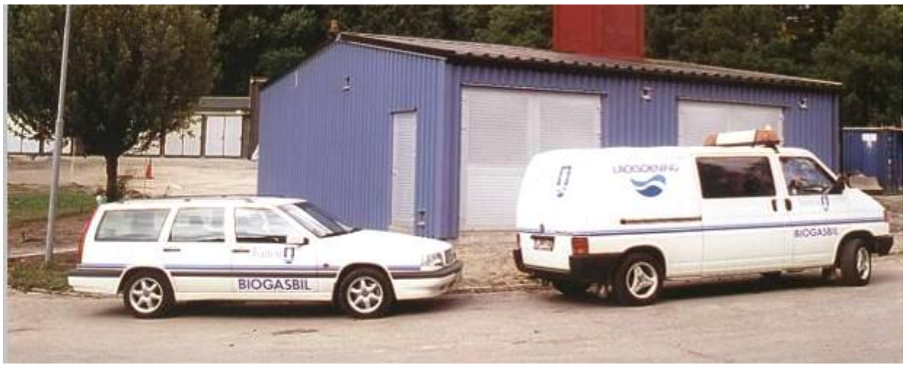
Picture 9. CBG bus in city of Stockholm



A single bus consumes on average 140 to 160 Nm^3/day of CBG compared to 70 to 80 Nm^3/day for trucks and 5 to 10 Nm^3/day for smaller cars (except taxis etc.) Even if the additional cost for a CBG bus is high compared to a diesel-fuelled bus, the fuel cost will still make the CBG option cost-effective, over the life time of the bus, for the bus owner.

A substantial advantage that CBG has compared to other clean cars in Sweden is that the variety of vehicles offered is great, not only small private cars but also cars for commercial use.

Picture 10. Service cars used by Stockholm Water in front of pilot plant, 1996



As mentioned above, Sweden established a quality standard early on for CBG, which helped a lot since the vehicle producers had a well-defined specification to meet, valid for all the CBG producers.

Picture 11. Waste handling truck

In some rare cases, “old” vehicles were converted to biogas operation, but due to Swedish legislation, this has been difficult and because of that notvery popular.

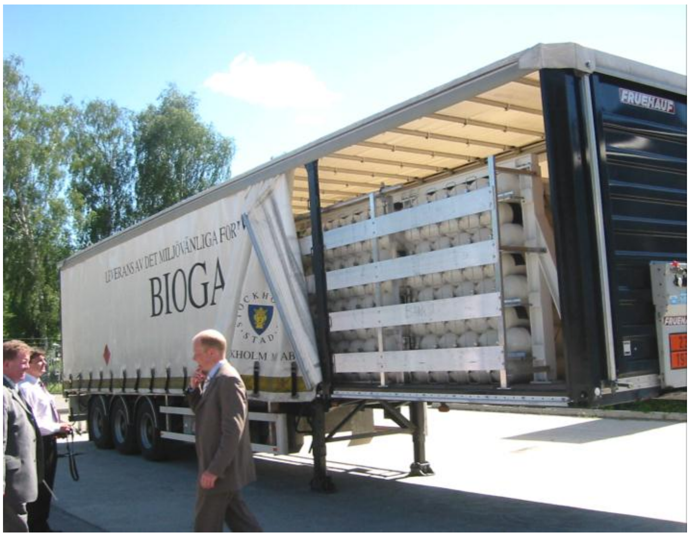
A major obstacle has been the uncertainty of the emission level of the vehicles. Today, most vehicles operating in Stockholm are produced by original equipment manufacturers (OEMs), i.e. by the vehicle manufacturers themselves.

The distribution of CBG from Bromma is carried out as compressed gas. In addition, some vehicles are fuelled on site by CBG from a dispenser at the high-pressure storage. The CBG is distributed to remote filling stations in compressed form on trailers. Three types of systems have been used, of which the AGA swap-body units is the only system used presently.

The hydraulic trailer was developed to refill the filling stations quickly using its own hydraulic system. The capacity was 1 400 Nm^3 of CBG in 20 minutes. It opened the possibility to use a simple 3-bank system for small filling stations without additional stationary compressors. In addition, it was approved for delivering CBG to the filling stations in the centre of the city. One disadvantage was the limited gas volume per delivery that made the trailer suitable for short distribution distances only.

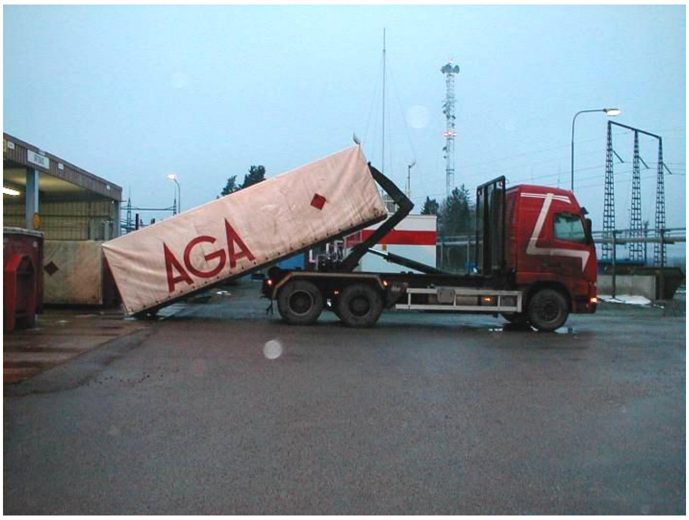
A larger trailer was procured with capacity to carry 7 000 Nm^3 of CBG and it was used to distribute to more remote fuelling stations. It was also used as a back-up system in between the production plants on temporary occasions to maintain a secure supply of biogas to customers. These two trailer types became uneconomical when the third system was introduced based on containers filled with gas bottles.

Picture 12. Large gas trailer



The AGA swap-body units with a capacity of 1 900 Nm^3 could be left on site both at the production plant and at the filling station. It enabled the possibility of a new rational way to distribute CBG at a lower cost. The system is presently in use for all the filling stations in Stockholm, which are not connected to a production plant by pipelines.

Picture 13. AGA swap-body unit



The Henriksdal plant supplies a bus depot through a 4-bar pipeline. The tunnel for the 4-bar pipeline has been drilled through the Henriksdal bare hillock, under the Hammarby canal and finally it ends up at the South bus depot.

In Rome, Malgrotta, the main problem for the operation of the trucks related to the fuel input system in the vehicles due to variation of the specification of the biogas. Considerable efforts were spent on engine maintenance of the CBG fuelled waste collection trucks (converted from gasoline fuelling). The variation of the upgraded biogas depended on quality variations of the raw gas from the landfill and was in first hand seasonal, relating to seasonal variation of the dumped municipal solid waste. This is a problem that must be considered for the future, if biogas from municipal waste is to be used for vehicle purposes,

Other disadvantages observed by the drivers using the biogas from Malgrotta were:

- Increased energy consumption
- Limited operational range (additional storage tanks were needed in vehicles to meet the necessary operation range.

- Reduced power compared to diesel fuelled engines

Picture 14. AMA Biomethane waste trucks

5. Positive experiences

In Stockholm, the use of biogas fuel is likely to have a positive impact on the air quality in the city centre. That is the area, which has the highest human exposure to air pollution. Furthermore, it is of great importance for the environment, as well as the economy, that methane, which previously was flared, especially during the summertime, can be sold and used for vehicle purposes today.

Today, it is also notable, when almost all produced biogas is used for vehicle purposes, that the change at the municipal sewage plants from internal heat production, using biogas, to heating by district heating has increased the consciousness of energy efficiency and energy costs. Since sewage plants have to buy energy today, the total energy cost for the plants has been reduced by approximately 30 %.

Concerning costs, it is also obvious how the knowledge and experiences gained over a period of 10 years has lead to a substantial decrease in cost for operation and maintenance.

One very encouraging experience in Stockholm was the positive reaction from drivers, as well as people in common, about the use of biogas.

Concerning Lille, it is notably thanks to the Marquette pilot experiment that LMCU wanted to replace its bus fleet to CNG and CBG operation, to present a 100 % clean public transport offer.

The decision in 2004 to recover 100 % of the biogas produced at the Organic Recovery Center and to upgrade it into vehicle fuel also is a result from the Marquette experiment.

Advantages reported from Rome are:

- Low levels of harmful emissions in the exhaust gases (considerably lower than Euro 3 requirements)
- Low noise level – low sound emissions (suitable for night operation).
- Low particulate levels in exhaust gases

Compared to a diesel fuelled vehicle the average economical savings over the vehicles life cycle in Rome were estimated to in the order of 20 %. This mainly due to reduced fuel cost compared to diesel cost and even if the price for the gas vehicle was approximately 40 % more than a comparable diesel fuelled vehicle and with a higher fuel consumption compared to a diesel fuelled one. However, this was a result of a very low biogas price, because of a huge amount of biogas available from the landfill.

6. Costs

6.1 Lille

In Lille, the building of the pilot plant was an experimental operation, without a precisely detailed preliminary budget.

However, in euros of 1997, the investments balance sheet was:

- Carcassing	106 565
- Gas treatment unit	413 409
- Buses transformation	375 941 (for 7 buses)
- Studies	330 988
TOTAL	**1 226 633 euros**

Furthermore, in euros of 1997, the operational cost balance sheet was (for the period August 1996-May 1997) was:

- Water and electricity:	2 600 (3,8 euros/running hour)
- Work pieces and useable goods:	7 600 (11,3 euros/running hour)
- Maintenance staff:	10 500 (15,4 euros/running hour)
- Daily maintenance staff and exploitation staff:	11 900 (17,4 euros/running hour)
TOTAL :	**32 600 euros**
	47,9 euros/running hour

6.2 Stockholm

6.2.1 Bromma

The initial budgets for the Bromma upgrading facilities of phase 1, as well as phase 2, both had to be increased over time.

The total investment cost for the Bromma plant, phase 1 and 2, was approximately 4 340 000 Euros (excluding subsidies).

Phase 2 had a first increase based on a more expensive construction cost followed by an incident in Norway that forced the process contractor into bankruptcy. The cost to finish the project with a new contractor simply became much more expensive (about 100 kEuros) than what could have been foreseen from the start.

Today, the total operational costs per year for the Bromma plant can be estimated to:

Electricity	120 000 Euros
Service and maintenance	75 000 Euros
Internal staff cost for service and maintenance (½ hour per day)	65 000 Euros
Total	**260 000 Euros**

6.2.2 Henriksdal

The total investment cost (including cots for LNG storage and parts of the biogas pipelines to the bus depot and Hammarby Sjöstad) for the Henriksdal upgrading plant can be estimated to almost 11 million Euros (excluding subsidies).

6.3 Gothenburg

The budgetary investment cost in Gothenburg, including compressors to transport the biogas to the plant, building, upgrading plant end equipment for propane was fixed to 4 356 000 Euros.

Budgetary operational, maintenance and capital cost for upgraded biogas was calculated to be 0,4 EUR/Nm^3 .

6.4 Bern

The investment cost in Bern is approximately 1 million Euro.

This amount is mainly financed by Energi wasser Bern (EWB).. In turn the first 15 MWh/a is delivered to a reduced price, including operational costs

7. Recommendations to new parties planning to upgrade biogas to fuel grade quality

Below, some recommendations to new parties planning to start upgrading of biogas are listed without any prioritisation.

The list is based on answers to the previously mentioned inquiry carried out in Lille and Stockholm.

1. It is necessary to obtain exact figures for (i.e. quantitatively) the potential for biogas production (and the feedstock).
2. It is also necessary to be aware that the technologies used often needs adjustment periods..
3. Do not hesitate to overproportion the infrastructures to be sure that the objectives can be reached (considering biogas quality) and also to ask the infrastructure builder for some kind of results guarantee.
4. Pay attention to the climate impact on exterior infrastructures. For these technologies, extreme ambient conditions such as cold or warm weather make the pilot unusable if it is located outdoors without any insulation.
5. Try to take into account the knowledge gained by someone who has built and operated a plant similar to the one that is planned. Visit such a plant and try to learn as much as possible from their work. Do not try to invent the wheel one more time. It is just time-consuming and it is also expensive.
6. Be exact and detailed in your tender specification documents, not at least concerning demand on the choice of materials, as well demand on the equipment and the specific processes.
7. Put up a demand in your tender document concerning the dryness of the gas – at least a dew point of –30^{o}C at 250 bar is desirable.

1)

Appendix

Matrices comparing upgrading and cleaning technologies

Conventional upgrading technologies

Technology / ***Parameters***	***PRESSURE SWING ABSORPRION***	**Absorption**			
		Water scrubbing		**Organic solvents**	
Active fluid or material	Activated carbon or Zeoloites	Water		Poly-ethylene glycol	Mono ethanol amine (MEA)
Pressurized/Compressed gas	Yes, 5-7 bar	Yes		Yes	Atmospheric pressure
Temperature					
Drying of gas before upgrading	Yes	No		Yes	No
Methane content in upgraded gas	> 97 %	97 – 99 %		98 –99 %	98 – 99 %
Methane losses	< 2 % *	< 2 %*		< 2 %	< 0,1 %
Sensitive to impurities	Yes, H_2S	No		Yes, H_2S cleaning of the raw gas recommended	Yes, H_2S cleaning of the raw gas recommended
Water in upgraded gas/ gas drying necessary	No	Yes		Yes	Yes
Approximate accessibility	95 %	95 %		95 %	
Time for daily supervision	30 minutes	30 minutes		30 minutes	
Time for yearly service and maintenance (internal personnel)	25 - 150 hours	25 – 150 hours		25 – 150 hours	
Electricity consumption excluding high pressure compression kWh/ m^3 upgraded gas**. Figures from *plant owner*	0,5 – 0,6	0,3 – 0,6		0,4	
Electricity consumption excluding high pressure compression kWh/m^3 upgraded gas***. Figures from *equipment manufacturer*	0,15 – 1,0	0,45 – 0,9		0,45 – 0,9	0,15
Water consumption M^3 /hour	None	Recirculating water system: Medium	Through flow water system: High	Low	Low
Consumption of chemicals	Low	Low	Low	High	High

* Equipment manufacturer figures. Higher methane losses has been noticed at some plants
** Depending on methane content in raw gas and dimensioning capacity

*** Depending on absorption pressure and dimensioning capacity

New upgrading technologies

Technology / ***Parameters***	**Membrane separation**		**Cryogenic separation**	**In-situ methane enrichment**
	Gas to liquid	Gas to gas		
Active fluid or material	e.g. Amines	____	__________	Air
Pressurized/Compressed gas	Atmospheric pressure	Yes, > 20 bar or 8 – 10 bar	Yes, > 5 bar	Atmospheric pressure
Temperature			- 45°C to –110 °C	
Water content in raw gas accepted			No	
Methane content in upgraded gas			> 94 % Technology for LNG production > 99 %	95 %
Methane losses			< 2 % *	< 2 % *
Sensitive to impurities	Yes, H_2S		Yes, H_2S	
Water in upgraded gas/ gas drying necessary				
Approximately accessibility				
Time for daily supervision				
Time for yearly service and maintenance				
Electricity consumption excluding high pressure compression kWh/ m^3 upgraded gas**. Figures from *plant owner*				
Electricity consumption excluding high pressure compression kWh/ m^3 upgraded gas***. Figures from *equipment manufacturer*				
Water consumption M^3 /hour	0,15			
Consumption of chemicals				

* Equipment manufacturer figures. However, measurements often shows substantially higher emissions level, up to 10 % and in some specific case as much as 18 %.

** Depending on methane content in raw gas and dimensioning capacity

*** Depending on absorption pressure and dimensioning capacity

Gas cleaning technologies

Hydrogen Sulphide (H_2S)

Contaminant / *Gas cleaning Technology*	**Hydrogen Sulphide (H_2S)**
Internal biological desulphurisation	Adding 2 – 6 % air into the digestion chamber. Up to 95 % reduction (less than 50 ppm)
Biological filters	Separate reaction chamber with carrier material. Adding air. Over 99 % reduction (Less than 50 to 100 ppm.)
Iron chloride	Adding Fe Cl_2 to the digestion chamber slurry. Reduction to 100 – 150 ppm
Impregnated activated carbon	Separate unit containing potassium doted carbon. Normally used before a PSA upgrading system.
Iron hydroxide or Iron oxide	Separation in separate chambers containing iron oxide in form of steel wool, wood chips covered with iron oxide or pellets made of red mud (a waste product from aluminium production
Sodium hydroxide scrubbing	A water solution of sodium hydroxide is used for scrubbing of the gas.

Contaminant	Gas Cleaning Technology		
Halogenated Hydrocarbons	*Pressure Swing Adsorption (PSA)	*Absorption	
		Water Scrubbing	Organic solvents
Siloxane	Activated Carbon (expensive)	Absorption in a liquid mixture of hydrocarbons	Cooling (-25°C gives approximately 26 % reduction efficiency while -70°C gives approximately 99 % reduction efficiency
Water	Refrigeration (Compression and cooling with a heat exchanger resulting in water condensation)	Adsorption on silica gel or aluminium oxide (suitable for gas for vehicle purpose with low dew point)	Absorption in glycol or hygroscopic salts
Oxygen and Nitrogen	* Pressure Swing Adsorption (PSA) Low efficiency	** Membrane separation Low efficiency	

* See description of today used upgrading technologies for more information

* See description of today used upgrading technologies for more information

** See description of the most promising and closest to market introduction upgrading technologies for more information

Costs

Technology / ***Parameters***	**Pressure Swing Adsorption**	**Absorption**		
		Water scrubbing	**Organic solvents**	
			Poly-ethylene glycol	***Mono ethanol amine (MEA)***
Investment cost 300 Nm^3 per hour of raw gas	1 Million Euros	1 Million Euros	1 million Euros	
Operational cost 200 Nm^3 raw gas per hour	< 1,5 Euro cents per kWh upgraded gas	<1,5 Euro cents per kWh upgraded gas	< 1,5 Euro cents per kWh	
Grand total cost for upgrading < 100 Nm^3 raw gas per hour	3,2 – 4,3 Euro cents per kWh upgraded gas	3,2 – 4,3 Euro cents per kWh upgraded gas	3,2 – 4,3 Euro cents per kWh upgraded gas	
Grand total cost for upgrading 200 - 300 Nm^3 raw gas per hour	1,1 – 1,6 Euro cents per kWh upgraded gas	1,1 – 1,6 Euro cents per kWh upgraded gas	1,1 – 1,6 Euro cents per kWh upgraded gas	

References (matrices):

Biogas Upgrading and Utilisation, IEA Bioenergy, Task 24: Energy from biological conversion of organic waste.

Utvärdering av uppgraderingstekniker för biogas, SGC rapport 142, Margareta Persson Lunds Tekniska Högskola, November 2003

Nya Renings- och Uppgraderingstekniker för Biogas, SGC rapport 163, Johan Benjaminsson, Linköpings Tekniska Högskola, april 2006