

# Biogas Upgrading to Vehicle Fuel Standards and Grid Injection

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## IEA Bioenergy

### Task 37 - Energy from Biogas and Landfill Gas

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## Introduction

During anaerobic digestion, i.e. degradation in the absence of oxygen, organic material is decomposed by bacteria forming digestate, an excellent fertilizer, and biogas, a mixture of carbon dioxide and methane. Anaerobic digestion (AD) has been successfully applied in recycling of biowaste and agricultural wastes, industrial wastewater treatment, stabilisation of sewage sludge and landfill management.

Today, farm-based manure facilities are perhaps the most common use of AD-technology. By the end of 2005 17 million family-sized low-technology digesters were used in China to provide biogas for cooking and lighting. There are now over 3500 farm-based digesters operating in Europe and North America. Thousands of digesters help to anaerobically stabilise and thicken sewage sludge before it is used on agricultural land, dried and incinerated or landfilled. More than 2 000 high-rate anaerobic digesters are operated world-wide to treat organic polluted process waste water from beverage, food, meat, pulp and paper and milk industries.

Gas recovery from landfills has become a standard technology in most of the industrialised countries for energy recovery, environmental and safety reasons. Increasingly the gas is used in combined heat and power (CHP) engines or as a supplement to natural gas.

There are more than 250 plants operating or under construction using the organic fraction of source separated municipal solid waste (MSW) to produce a high quality compost or mechanically separated MSW to stabilise the organic fraction before landfilling. The total installed capacity is close to ten million tonnes.

The product of anaerobic digestion is a gas containing primarily methane and carbon dioxide, commonly called biogas. In small-scale installations, worldwide, the gas is primarily utilised for lighting and cooking. In larger units the gas can be used for co-generation (generation of heat and electricity), as vehicle fuel or as fuel in industrial processes.

The total European biogas production was in 2004 estimated to 50 TWh. This was a 43% increase from 2002. More than 55% of the biogas production comes from landfills and sewage sludge treatment but this is expected to change since deposition of organic material in landfills has to be reduced and is even banned in European countries. Instead biological treatment or incineration of organic material is steadily increasing.

A study (From biogas to energy: a European overview, 2001) performed by Solagro, predicts a production of 210 TWh by the year 2020. This can be compared to the total world gasoline production that in 2004 was 11'000 TWh.

The majority of the countries that participated at the conference of Kyoto and followers have ratified the individual goals for the reduction of CO<sub>2</sub>, set for each country. Transport is the sector where the highest increase occurs. The European Commission predicts a 50% increase in the emissions of greenhouse gases in the transport sector from 1990 to 2010. In year 2000 the greenhouse gas emissions

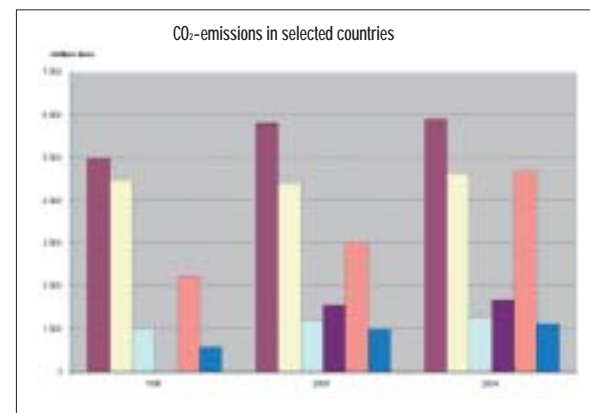


Kompostgas plant in Oetwil, Switzerland

had increased by almost 25% from the 1990 level. It is expected that 90% of the increase is attributable to the transport sector.

Alternative fuels might help considerably to reduce emissions. This has been recognised by a number of governments which brought forward programs and legislations. A new biofuel directive (2003/30/EC) from the European Commission was approved in 2003. This directive sets targets for the European Union to gradually replace fossil fuels by biofuels. The present targets are 2% biofuels by the year 2005 and 5.75% biofuels by the year 2010. In particular, biogas as a fuel could bring substantial reductions in greenhouse gases, particles and nitrogen oxide emissions, when replacing fossil fuels, like diesel or petrol.

In 2003, the European Parliament adopted the Directive 2003/55/EC, giving common rules for the natural gas market but also for biogas and other gases from biomass in so far such gases can technically and safely be injected into, and transported through the natural gas system.



## Biogas Composition

Biogas produced in AD-plants or landfill sites is primarily composed of methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) with smaller amounts of hydrogen sulphide (H<sub>2</sub>S) and ammonia (NH<sub>3</sub>). Trace amounts of hydrogen (H<sub>2</sub>), nitrogen (N<sub>2</sub>), saturated or halogenated carbohydrates and oxygen (O<sub>2</sub>) are occasionally present in the biogas. Usually, the gas is saturated with water vapour and may contain dust particles and organic silicon compounds (e.g. siloxanes). Typical compositions of different kinds of biogas and natural gas are shown in the table below. The raw gas is in all cases saturated with moisture.

## Composition and parameters of gas from different sources

| PARAMETER                            | UNIT                | LANDFILL GAS | BIOGAS FROM AD | NORTH SEA NATURAL GAS | DUTCH NATURAL GAS |
|--------------------------------------|---------------------|--------------|----------------|-----------------------|-------------------|
| Lower heating value                  | MJ/nm <sup>3</sup>  | 16           | 23             | 40                    | 31,6              |
|                                      | kWh/nm <sup>3</sup> | 4,4          | 6,5            | 11                    | 8,8               |
|                                      | MJ/kg               | 12,3         | 20,2           | 47                    | 38                |
| Density                              | kg/nm <sup>3</sup>  | 1,3          | 1,2            | 0,84                  | 0,8               |
| Higher Wobbe index                   | MJ/nm <sup>3</sup>  | 18           | 27             | 55                    | 43,7              |
| Methane number                       |                     | > 130        | >135           | 70                    | –                 |
| Methane                              | vol-%               | 45           | 63             | 87                    | 81                |
| Methane, variation                   | vol-%               | 35–65        | 53–70          | –                     | –                 |
| Higher hydrocarbons                  | vol-%               | 0            | 0              | 12                    | 3,5               |
| Hydrogen                             | vol-%               | 0–3          | 0              | 0                     | –                 |
| Carbon oxide                         | vol-%               | 0            | 0              | 0                     | 0                 |
| Carbon dioxide                       | vol-%               | 40           | 47             | 1,2                   | 1                 |
| Carbon dioxide, variation            | vol-%               | 15–50        | 30–47          | –                     | –                 |
| Nitrogen                             | vol-%               | 15           | 0,2            | 0,3                   | 14                |
| Nitrogen, variation                  | vol-%               | 5–40         | –              | –                     | –                 |
| Oxygen                               | vol-%               | 1            | 0              | 0                     | 0                 |
| Oxygen, variation                    | vol-%               | 0–5          | –              | –                     | –                 |
| Hydrogen sulphide                    | ppm                 | < 100        | < 1000         | 1,5                   | –                 |
| Hydrogen sulphide, variation         | ppm                 | 0–100        | 0–10000        | 1–2                   | –                 |
| Ammonia                              | ppm                 | 5            | <100           | 0                     | –                 |
| Total chlorine (as Cl <sup>-</sup> ) | mg/nm <sup>3</sup>  | 20–200       | 0–5            | 0                     | –                 |

One very important factor in gas utilisation is the gas Wobbe index. This is determined by the equation below.

$$W = \frac{H}{d}$$

$W$  = heating value  
 $d$  = relative density

The heating value of biogas is determined mainly by the methane content in the gas. The higher heating value gives the energy that is released when one normal cubic meter (nm<sup>3</sup>) of biogas is combusted and the water vapour formed in the combustion is condensed. The lower heating value shows the energy formed when the water vapour is still not condensed. Just as there is a lower and higher heating value there is also a lower and higher Wobbe index. Relative density is the quotient of gas and air density. The methane number is a parameter that describes the gas resistance to knocking when used in a combustion engine. Methane has per definition a methane number of 100 and H<sub>2</sub> a methane number of zero. CO<sub>2</sub> increases the methane number because it is a non combustible gas with a high knocking resistance. Upgraded biogas therefore has a methane number higher than 100.



## Typical contaminants in biogas

Landfill gas may contain more than 500 different contaminants such as halogenated hydrocarbons, higher hydrocarbons and aromatic compounds. Landfill gas and gas from digestion of sewage sludge may also contain siloxanes that may cause severe problems in downstream utilisation.

## Sulphur gases

Biogas and, especially, landfill gas can contain a variety of sulphur compounds, such as sulphides, disulphides and thiols. Especially oxidized sulphur compounds (sulphate and sulphite) are corrosive in the presence of water.

It has to be removed in order to avoid corrosion in compressors, gas storage tanks and engines. The main sulphur compound in biogas is hydrogen sulphide. It is reactive with most metals and the reactivity is enhanced by concentration and pressure, the presence of water and elevated temperatures.

## Halogenated compounds

Halogenated compounds (e.g. carbon tetrachloride, chlorobenzene, chloroform and trifluoromethane) are often present in landfill gas, however, only rarely in biogas from digestion of sewage sludge or organic waste.

Halogens are oxidized during the combustion process. The combustion products are corrosive, especially in the presence of water and can cause corrosion in downstream pipes and applications. They can also initiate the formation of PCDDs and PCDFs (dioxines and furans) if the combustion conditions (temperature and time) are favourable.

Most halogenated species in landfill gas are the result of direct volatilisation from solid waste components and their presence depends on vapour pressure relationships under landfill conditions. The most common fluorinated contaminants are the chloro-fluorocarbons (CFCs), which were widely used as refrigerants, propellants, and in insulating foams until their use was forbidden or reduced in the late 1980s. The most abundant CFCs in landfill gas are CFC-12 (dichlorodifluoromethane) and CFC-11 (trichlorofluoromethane). These appear to persist at low concentrations in landfills due to their slow volatilisation from old waste.

## Siloxanes

Siloxanes are volatile silicones bonded by organic radicals. They occur in landfill gas and gas from digestion of sewage sludge. These originate from different kinds of consumer products (e.g. shampoo, detergents and cosmetics.)

Siloxanes are converted during combustion to inorganic siliceous deposits in downstream applications. The amount of silica has to be reduced to a minimum, especially in engine applications. Siliceous deposits on valves, cylinder walls and liners are the cause of extensive damage by erosion or blockage.



Siloxane deposits at the cylinder of a CHP engine

Silicon compounds may also reach the lubrication oil requiring more frequent oil changes. The increased use of cosmetics and other silicon containing products means that more frequent siloxane monitoring in the fuel gas is required. There is though no standard method for siloxane monitoring and discrepancies exist between results with different measuring methods.

#### Ammonia

High concentrations of ammonia are a problem for gas engines, and are often limited by manufacturers of gas engines. Normally up to 100 mg/nm<sup>3</sup> ammonia can be accepted. The combustion of ammonia leads to the formation of nitrous oxide (NO<sub>x</sub>).

#### Dust and particles

All biogas plants must be equipped with some kind of filter or/and cyclone for reduction of the amounts of particles in the gas. Filters not only remove particulates but also reduce the content of droplets of water or oil. Filters with a 2 – 5 micron mesh size are normally regarded as appropriate for most downstream applications.

## National gas standards

Biogas can either be used directly on the site where it is generated or distributed to external customers via separate pipelines. After proper upgrading it might be fed into the distribution grid for natural gas. The deregulation of the natural gas market in Europe has opened the possibility to find new customers for upgraded biogas via the gas grid.

There is no international technical standard for biogas injection but some countries have developed national standards and procedures for biogas injection. MARCO-GAZ, the technical association of the European Natural Gas Industry has adopted a recommendation concerning technical and gas quality requirements for delivery of non-conventional gases e.g biogas into gas networks. The recommendation will be official in 2007.

Injecting biogas into the gas grid sometimes raise concerns about the risk of transmitting disease via the gas. The Swedish Institute of Infectious Disease Control, National Veterinary Institute and the Swedish University of Agricultural Science have evaluated this risk (Identification of the microbiological community in biogas systems and evaluation of microbial risk from gas usage. ELSEVIER, 2006). The study concluded that the risk of spreading disease via biogas was judged to be very low; the number of micro organisms found in biogas was equal to the level found in natural gas.

#### Sweden

In 1999 Sweden has developed a national standard for biogas as vehicle fuel on request of the Swedish vehicle manufacturers as a design basis for fuel- and engine systems. The main parameters of the standard are described in the table below. Motor octane number is a

Gas buses in the city: low emissions and low noise.



definition of the resistance to knocking of fuels. The Swedish standard is also applied when injecting biogas into the natural gas grid. Additional demands concerning heating value are covered by addition of propane to the gas.

#### Swedish national standard for biomethane

| PARAMETER                                       | UNIT                | DEMAND IN STANDARD                       |
|---|---------------------|--|
| Lower Wobbe index                               | MJ/nm <sup>3</sup>  | 43,9 – 47,3 <sup>1</sup>                 |
| MON (motor octane number)                       | -                   | >130 (calculated according to ISO 15403) |
| Water dew point                                 | °C                  | <T <sup>2</sup> -5                       |
| CO <sub>2</sub> +O <sub>2</sub> +N <sub>2</sub> | vol-%               | <5                                       |
| O <sub>2</sub>                                  | vol-%               | <1                                       |
| Total sulphur                                   | mg/ nm <sup>3</sup> | <23                                      |
| NH <sub>3</sub>                                 | mg/ nm <sup>3</sup> | 20                                       |

#### Switzerland

Biogas is injected into the natural gas grid at several locations in Switzerland. Two different qualities are allowed in the Swiss regulations (G13): gas for limited injection and gas for unlimited injection. The restrictions for gas for unlimited injection are of course more severe than the restrictions for limited injection.

#### Swiss national standard for unlimited gas injection

| PARAMETER             | UNIT                | DEMAND IN STANDARD |
|-----------------------|---------------------|--------------------|
| Methane content       | Vol-%               | >96                |
| Gas relative humidity | phi                 | <60%               |
| Dust                  | -                   | Technically free   |
| CO <sub>2</sub>       | vol-%               | <6                 |
| O <sub>2</sub>        | vol-%               | <0,5               |
| H <sub>2</sub>        | vol-%               | <5                 |
| H <sub>2</sub> S      | mg/ nm <sup>3</sup> | <5                 |
| S                     | mg/ nm <sup>3</sup> | <30                |

#### Swiss national standard for limited gas injection

| PARAMETER              | UNIT                | DEMAND IN STANDARD |
|------------------------|---------------------|--------------------|
| Methane content        | Vol-%               | >50                |
| Gas relative humidity  | phi                 | <60%               |
| Dust                   | -                   | Technically free   |
| CO <sub>2</sub>        | vol-%               | <6                 |
| O <sub>2</sub>         | vol-%               | <0,5               |
| H <sub>2</sub>         | vol-%               | <5                 |
| H <sub>2</sub> S       | mg/ nm <sup>3</sup> | <5                 |
| S (without odouration) | mg/ nm <sup>3</sup> | <30                |

#### Germany

Germany has a standard for biogas injection (G262) that has been elaborated in cooperation between the German Water and Gas Association and the German Biogas Association. The standard is based on the German standard for natural gas, DVGW G260. The main requirements in the standard are stated below (for injection into natural gas grids with high heating value).

The German standards allow injection of two types of gas, gas for limited injection and gas for unlimited injection. Unlimited injection of upgraded biogas in H-gas grids is possible if the cited concentrations are maintained. The German standard also

<sup>1</sup> Corresponds to 95 – 99% methane

<sup>2</sup> T= ambient temperature



Gas injection into the natural gas grid in Samstagern, Switzerland

requires the biogas producer to present at safety data sheet that describes any health hazards in connection to the handling of the biogas.

#### Requirements for gas injection according to German standard G260/G262

| PARAMETER          | UNIT                | DEMAND IN STANDARD   |
|--------------------|---------------------|--|
| Higher Wobbe index | MJ/nm <sup>3</sup>  | 46,1 – 56,5 <sup>1</sup> in H gas <sup>2</sup> grids<br>37,8 – 46,8 <sup>3</sup> in L gas <sup>2</sup> grids |
| Relative density   | -                   | 0,55 – 0,75  |
| Dust               | -                   | Technically free   |
| Water dew point    | °C                  | <1 <sup>4</sup>  |
| CO <sub>2</sub>    | vol-%               | <6   |
| O <sub>2</sub>     | vol-%               | <3 (in dry distribution grids)   |
| S                  | mg/ nm <sup>3</sup> | <30  |

#### France

Gaz de France has in 2004 produced a de facto standard for gas injection into the national gas grid. The standard has more strict limits on oxygen than the other standards and also comprises a number of limits for heavy metals and halogens.

#### French national regulation for gas injection

| PARAMETER             | UNIT               | DEMAND IN STANDARD  |
|-----------------------|--------------------|---|
| Higher heating value  | MJ/nm <sup>3</sup> | H gas: 38,52 to 46,08<br>L gas: 34,2 to 37,8                        |
| Higher Wobbe index    | MJ/nm <sup>3</sup> | H gas: 48,24 to 56,52<br>L gas: 42,48 to 46,8                       |
| Hydrocarbon dew point | °C                 | < -5 from 1 to 80 bar   |
| Water dew point       | °C                 | < -5 at MOP downstream from injection point (Gergwater correlation) |
| CO <sub>2</sub>       | vol-%              | < 2   |
| Dust                  | mg/nm <sup>3</sup> | < 5   |
| Total sulphur         | mg/nm <sup>3</sup> | < 100 instant content<br>< 75 annual average                        |
| O <sub>2</sub>        | ppmv               | < 100   |
| Hg                    | mg/nm <sup>3</sup> | < 10 (Natural gas)<br>< 50 (Liquefied Natural Gas)                  |
| Cl                    | mg/nm <sup>3</sup> | < 1   |
| F                     | mg/nm <sup>3</sup> | < 10  |
| H <sub>2</sub>        | %                  | < 6   |
| CO                    | %                  | < 2   |

<sup>1</sup> Corresponds to >97.5% methane

<sup>2</sup> high heating value gas

<sup>3</sup> Corresponds to 87 – 98.5% methane

<sup>4</sup> low heating value gas

<sup>5</sup> t= ground temperature

## Gas Utilisation

Gas is an excellent fuel for a large number of applications and can also be used as raw material for the production of chemicals. Biogas can be used in more or less all the applications that are developed for natural gas. For some of the applications the biogas may have to be upgraded. Injection of biogas into the natural gas grid will result in an improved security of supply. This is important since dependence on imported natural gas is increasing and only 2/3 of the European gas consumption is covered by gas from the EC. The benefits of gas as a fuel have resulted in increased use. Natural gas accounts for 25% of the total energy consumption in the EU25 countries (2005, www.bp.com). Additional amounts of natural gas will have to be imported to Europe already before 2010. Estimates by Eurogas indicate that natural gas import to the (former) EU15 has to be increased by 190 Mtoe before the year 2020. The increased demand will of course also be reflected by increasing gas prices.

There are four basic ways biogas can be utilised:

- Production of heat and steam
- Electricity production/ co-generation
- Vehicle fuel
- Production of chemicals

The main utilisation of biogas is governed by national frameworks like the tax system, subsidies, availability of gas and heat grids. Worldwide, biogas is mainly used for electricity production whereas in Sweden and in Switzerland a growing portion of the biogas is used in the transport sector.

The major driver defining the way of biogas utilisation is the compensation of the energy, i.e. electricity or (upgraded) biogas. Most of the European countries have increased feed-in tariffs for electricity. Front runners are Germany and Austria with feed-in tariffs for biogas up to 21.5 € cents per kWh.

Sweden on the other hand has a history of low electricity prices compared to the rest of Europe. It has therefore become the market leader for biogas as vehicle fuel. The rate of growth has been rapid, for example 25% between 2004 and 2005. The development has been driven by several factors including tax exemption, government investment programme, reduction on valuation tax and free parking in several cities.

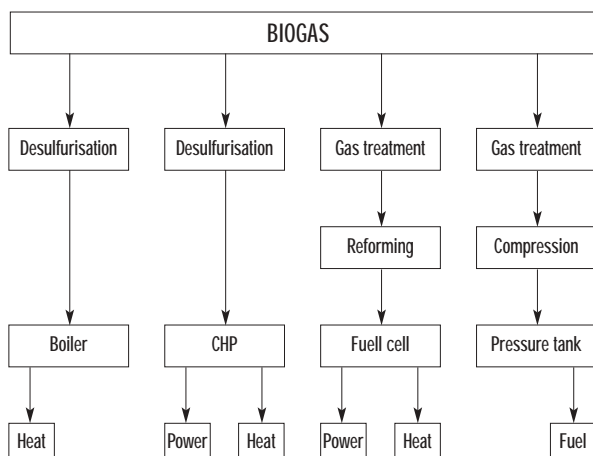
The most common applications for biogas are heating and power generation. Using biogas as vehicle fuel and injecting the gas into the gas grid are applications that reach more and more interest.

### Production of heat

The most common use of biogas from small-scale plants in developing countries is for cooking and lighting. Conventional gas burners and gas lamps can easily be adjusted to biogas by changing the air to gas ratio. In more industrialized countries boilers

are present only in a small number of plants where biogas is used as fuel only without additional CHP. In a number of industrial applications biogas is used for steam production.

Burning biogas in a boiler is an established and reliable technology. Low demands are set on the biogas quality for this application. Pressure usually has to be around 8 to 25 mbar. Furthermore it is recommended to reduce the level of hydrogen sulphide to below 1 000 ppm, this allows to maintain the dew point around 150 °C.



Biogas can be used in all natural gas appliances provided that upgrading of the gas quality is carried out.

## Power generation / Combined Heat and Power (CHP)

Biogas is the ideal fuel for generation of electric power or combined heat and power. A number of different technologies are available and applied.



Larger CHPs (> 200kW) usually are pure gas engines with spark ignition

## Internal combustion

The most common technology for power generation is internal combustion. Engines are available in sizes from a few kilowatts up to several megawatts. Gas engines can either be SI-engines (spark ignition) or dual fuel engines.

Dual fuel engines with injection of diesel (10% and up) or sometimes plant oil are very popular in smaller scales because they have good electric efficiencies up to guaranteed 43%. On the other hand they have higher emissions unless they use a SNCR catalyst. Another advantage is the easy start-up of the biogas plant because heat and electricity can be produced from scratch by using diesel only.

SI-engines are equipped with normal ignition systems and a gas/air mixing system that provides a combustible mixture to the engine. SI-engines can either be stoichiometric or lean-burn engines. The stoichiometric engines operate without air excess and can thereby also use a three-way catalyst that is common in light duty vehicles. Lean burn engines are more common in larger sizes and generally have a higher efficiency.

## Gas turbines

Gas turbines are an established technology in sizes above 800 kW. In recent years also small scale engines, so called micro-turbines in the range of 25 to 100kW have been successfully introduced in biogas applications. They have efficiencies comparable to small SI-engines with low emissions and allow recovery of low pressure steam which is interesting for industrial applications. Maintenance cost are very low.

## Fuel cells

Fuel cells have a potential to become the small scale power plant of the future. Fuel cell technology is 160 years old, which is more or less the same age as the combustion engine and the Stirling engine. Nevertheless, widespread commercial use is yet to be achieved. Fuel cells have a potential to reach very high efficiencies (>60%) and low emissions. Special interest for stationary biogas application is focussed on hot fuel cells operating at temperatures above 800°C particularly because the CO<sub>2</sub> does not inhibit the electrochemical process, but rather serves as an electron carrier. Two types of fuel cells are in an advanced stage of development: the solid oxide fuel cell (SOFC) for small applications of a few kW and the molten carbonate fuel cells (MCFC) operating in the range of 250kW and up.

| FEATURE          | PETROL ENGINE SI | DIESEL ENGINE JET IGNITION | DIESEL ENGINE SI | MICRO TURBINE |
|------------------|------------------|----------------------------|------------------|---------------|
| Efficiency [%]   | 24–29            | 30–38                      | 35–42            | 26–29         |
| Maintenance cost | High             | High                       | Medium           | Low           |
| Investment cost  | Low              | Medium (high)              | Medium           | High          |
| Power [kW]       | 5–30             | 30–200                     | >200             | <100          |
| Lifespan         | Low              | Medium                     | High             | High          |

Biogas can be used for generation of electricity in a number of different technologies.





## Biogas injection into the gas grid

Biogas can be injected and distributed through the natural gas grid since biogas like natural gas mainly consists of methane.

There are several incentives for using the gas grid for distribution of biogas. One important advantage is that the grid connects the production site with more densely populated areas which enables the gas to reach new customers. It is also possible to increase the production at a remote site and still use 100% of the gas. Furthermore injecting biogas into the gas grid improves the local security of supply. This is an important factor since most of the countries consume more gas than they produce.

As previously listed some countries like Sweden, Switzerland, Germany and France have a standard for injecting biogas into the natural gas grid. The standards have been set to avoid contamination of the gas grid or end use. Demands on Wobbe index have been set to avoid influence on gas measurements and end use.

In the standards there are limits on certain components for instance sulphur, oxygen, particles and water dew point. These demands are in most cases possible to achieve with existing upgrading processes. In some cases landfill gas can be difficult to upgrade to sufficient quality due to large content of nitrogen.

## Gas upgrading technologies

There are three major reasons for gas cleaning:

- fulfil the requirements of gas appliances (gas engines, boilers, fuel cells, vehicles etc.)
- increase the heating value of the gas
- standardisation of the gas

The gas quality requirements depend strongly on the utilisation

| APPLICATION             | H <sub>2</sub> S | CO <sub>2</sub> | H <sub>2</sub> O |
|-------------------------|------------------|-----------------|------------------|
| Gas heater (boiler)     | <1000 ppm        | no              | no               |
| Kitchen stove           | yes              | no              | no               |
| Stationary engine (CHP) | < 1000 ppm       | no              | no condensation  |
| Vehicle fuel            | yes              | yes             | yes              |
| Natural gas grid        | yes              | yes             | yes              |

Requirements to remove gaseous components depend on the biogas utilization.

Utilisation in stationary gas engines is a typical case where only contaminants have to be removed from the biogas. Most manufacturers of gas engines set maximum limits

of hydrogen sulphide, halogenated hydrocarbons and siloxanes in biogas. When using biogas for vehicle fuel all contaminants as well as carbon dioxide need to be removed to reach a sufficient gas quality.

There are several technologies available for removing contaminants from biogas and upgrading the gas to vehicle fuel or natural gas quality.

### Carbon dioxide removal

Before using biogas as vehicle fuel the level of carbon dioxide is reduced in the gas. It would be technically possible to run a vehicle on biogas without removing the carbon dioxide if the engine would be specially adjusted to it, but there are several reasons why carbon dioxide must be removed.

Removing carbon dioxide increases the heating value of the gas resulting in an increased driving distance for a specific gas storage volume. It also leads to a consistent gas quality between different biogas plants and a similar quality to natural gas.

Before adding biogas into the natural gas grid it is also common to remove carbon dioxide in order to reach the required Wobbe index of the gas. When removing carbon dioxide from the gas stream small amounts of methane are also removed. It is important to keep these methane losses low for both economical as well as environmental reasons since methane is a greenhouse gas 21 times stronger than CO<sub>2</sub>.

There are several different commercial methods for reducing carbon dioxide. Most common are absorption or adsorption processes. Other techniques that are used are membrane separation and cryogenic separation. One interesting method under development is process internal upgrading.

| PRINCIPLE  | NAME                            | TYPE OF REGENERATION | PRE TREATMENT                  | WORKING PRESSURE (BAR) |   |
|------------|---------------------------------|----------------------|--------------------------------|------------------------|---|
| Adsorption | Pressure Swing Adsorption (PSA) | Vacuum               | Water vapour, H <sub>2</sub> S | 4–7                    |   |
| Absorption | Water                           | None/Air stripping   | None                           | 7–10                   |   |
|            | Polyethylene glycol             | Air stripping        | Water vapour, H <sub>2</sub> S | 7–10                   |   |
|            | Mono ethanol amine (MEA)        | Heating              | H <sub>2</sub> S               | atmospheric            | General data for absorption and adsorption processes. |

### Absorption

Carbon dioxide and hydrogen sulphide can be removed from biogas through absorption processes. The different binding forces of the more polar CO<sub>2</sub> or H<sub>2</sub>S and the non-polar methane are used to separate these compounds.

### Water scrubbing

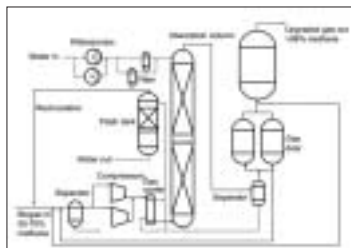
Water is the most common solvent in which case the process is called water scrubbing. Biogas is compressed and fed into the bottom of a column where it meets a counter flow of water. The column is filled with packings to create a large surface between gas and liquid. Carbon dioxide as well as hydrogen sulphide are more soluble in water than methane. The biogas which is brought out of the top of the column is enriched in methane and saturated with water. To reduce the water vapour the biogas needs to be dried.

The CO<sub>2</sub>-enriched water is brought to a flash tank where the pressure is reduced and most of the carbon dioxide is released. Sometimes the process is enhanced by air stripping or by vacuum. Air stripping brings oxygen into the system which is a problem when the gas is used as fuel or when it is fed into the grid. The gas released in the flash tank is recirculated to the inlet of the compressor. The process can use fresh water all the time. This is most common at sewage treatment plants where purified water is available. Hydrogen sulphide which is released to the air creates an emission problem. Some of the sulphur is accumulated in the water and can cause problems with fouling and plugging of pipework after some time of operation. It is therefore recommended that hydrogen sulphide is separated before hand.

Plugging in the absorption column due to organic growth can be an issue at these plants and therefore it is recommended to install automatic washing equipment for the column.



Water wash is one of the most common techniques for separating carbon dioxide from biogas.



Carbon dioxide has a higher solubility in water than methane. This permits separation of the two components in an absorption column.

### Organic solvents

Instead of water an organic solvent like polyethylene glycol can be used for the absorption of carbon dioxide. Selexol® and Genosorb® are trade names for the chemicals. In this solvent, like in water, carbon dioxide and hydrogen sulphide are more soluble than methane and the process proceeds in the same way as water scrubbing with regeneration. The main difference to water is that carbon dioxide and hydrogen sulphide are far more soluble in organic solvents than in water. Hence, a smaller upgrading plant can be built for the same gas capacity. In the process also water and halogenated hydrocarbons, which can occur in landfill gas, are separated. However a lot of energy is needed to regenerate the organic solvent from hydrogen sulphide and therefore it is often better to separate the hydrogen sulphide prior to the absorption.

Other organic solvents that can be used are alkanol amines like mono ethanol amine (MEA) or di-methyl ethanol amine (DMEA). The chemical is regenerated in a reverted chemical reaction usually driven by heat and/or 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 carbon dioxide and very little methane is removed. The gas is compressed and dried and can then be used for vehicles or distributed into the gas grid. The chemical is regenerated through heating with steam which has the disadvantage of being energy consuming.

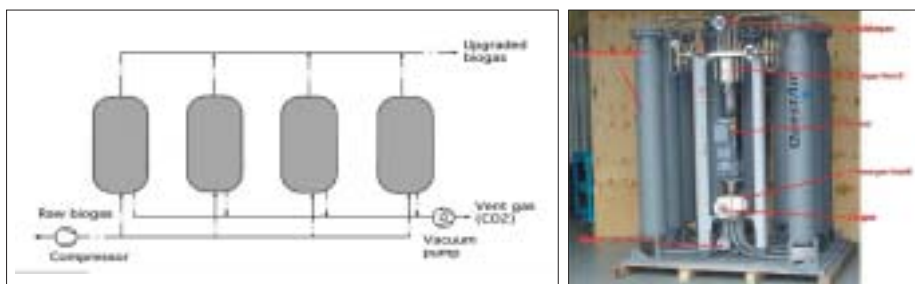
### Pressure Swing Adsorption

Adsorption of carbon dioxide on a material like activated carbon or molecular sieves can be used to separate carbon dioxide from the biogas. The selectivity of adsorption can be achieved with different mesh sizes. This method is named Pressure Swing Adsorption, PSA, since the adsorption takes place at elevated pressure and the material is regenerated through reducing the pressure and subsequent application of a light vacuum.

The process requires dry gas. Water vapour is usually condensed in a cooler. Hydrogen sulphide needs to be pre-separated before the gas is fed into the bottom of the adsorption vessel. This is done by an additional tank with activated carbon. Usually when its surface is saturated with hydrogen sulphide, the material is exchanged. Adding air to the biogas stream can extend the lifetime of the sulphide removal unit however, it bears the risk that there are traces of oxygen also in the upgraded biogas.

In the pressurized vessels carbon dioxide is adsorbed. The gas leaving the top of the vessel is enriched with methane. When the material in the vessel is saturated, biogas is led to a new vessel. There are several (most often four) vessels linked together to create a continuous operation and to reduce the energy need for gas compression. Regeneration of the saturated vessel is achieved through stepwise depressurisation. First the pressure is reduced through linking the vessel with an already regenerated vessel. Then the pressure is reduced to almost atmospheric pressure. The gas released in this step contains significant amounts of methane and is therefore recycled to the gas inlet.

Finally the vessel is completely evacuated with a vacuum pump. The gas that leaves the vessel in this step mainly consists of carbon dioxide which is in one system (Carbotech) released to the atmosphere. In another system (Questair/Verdesis) it is burned in a flox burner designed for low calorie gases. In the first system more upgraded biogas is produced whereas the second system needs less absorber surface and has no methane slip to the atmosphere.



### Membrane separation

There are different processes with membrane separation. Either it is a separation with a 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 liquid can be an amine and the system has high selectivity compared to solid membrane systems. Separation takes place at low pressure, approximately atmospheric pressure.

Membranes with gas phases on both sides can also be called dry membranes. The membrane either works at high pressure > 20 bar or at low pressures 8-10 bar. The separation is driven by the fact that different molecules of different size have different permeability through the membrane. Other important factors for the separation are pressure difference between the two sides of the membrane and temperature of the gas. Carbon dioxide and hydrogen sulphide pass through the membrane to the permeate side whereas methane is retained on the inlet side.

Also some methane passes through the membrane to the permeate stream. There is a conflict between high methane levels in the gas and at the same time a high methane recovery. High methane level in the upgraded gas can be achieved with larger size or several membranes in series. This on the other hand leads to high losses of metha-

ne into the permeate stream. If the permeate stream can be used for instance in a combined heat and power plant together with raw gas or in a flox burner, it is possible to utilise the methane that is lost in the process and at the same time reduce cost for investment and energy consumption for the upgrading.

The biogas is compressed and dried before being led to the membrane where carbon dioxide and some hydrogen sulphide are separated. Further separation of hydrogen sulphide is needed before the biogas can be used for vehicles or fed into the gas grid.

### Cryogenic separation

Methane has a boiling point of  $-160\text{ }^{\circ}\text{C}$  at atmospheric pressure whereas carbon dioxide has a boiling point of  $-78\text{ }^{\circ}\text{C}$ . This means that carbon dioxide can be separated from the biogas as a liquid by cooling the gas mixture at elevated pressure. Methane can be taken out in gas or liquid phase, depending on how the system is constructed. When also methane is condensed, nitrogen which has an even lower boiling point is separated and this is an advantage when dealing with landfill gas. The separated carbon dioxide is clean and can be sold. Until today (2006) this method has only been tested in pilot plants in Europe.

To avoid freezing and other problems in the cryogenic process water and hydrogen sulphide need to be pre-separated. The principle of cryogenic separation is that biogas is compressed and then cooled by heat exchangers followed by an expansion step for instance in an expansion turbine. The cooling and the expansion causes the carbon dioxide to condensate. Compression as well as chilling can be done in several steps. After carbon dioxide has been removed as a liquid the gas can be cooled further to condensate the methane.

### In-situ methane enrichment

Conventional techniques for separating carbon dioxide from biogas demand a lot of process equipment and the methods are usually suited for large plants in order to reach a sufficient economy. In-situ methane enrichment is a new technology under development in pilot-scale which promises a better economy also for smaller plants.

Sludge from the digestion chamber is led to a column where it meets a counter flow of air. Carbon dioxide that is dissolved in the sludge is desorbed. The sludge is led back to the digestion chamber. More carbon dioxide can now dissolve into the sludge resulting in methane enriched gas in the chamber.

The results from lab-scale tests in Sweden indicate that it is technically possible to construct a system that increases the methane content of the gas to 95% and still keep the methane losses below 2%.

### Removal of hydrogen sulphide

Hydrogen sulphide is formed from digestion of proteins and other material that contains sulphur. Since hydrogen sulphide is highly corrosive it is recommended to

separate it early in the biogas upgrading process. It can be removed in the digestion chamber, in the gas stream or in the upgrading process. Some of the most common methods for removing hydrogen sulphide are in fact internal, iron chloride dosing to the digester slurry or air/oxygen dosing to the digester.

#### Biological desulphurisation

Micro-organisms can be used to reduce the level of sulphide in biogas, by converting it to mainly elementary sulphur and some sulphate. The sulphur-oxidising micro-organisms mainly belong to the family of Thiobacillus. They are commonly present in the digestion material and thus don't have to be inoculated. Furthermore, most of them are autotrophic, which means that they use carbon dioxide from the biogas as a carbon source.

Oxygen needs to be added to the biogas for biological desulphurisation. Oxygen should be added in stoichiometric amounts and the level needed depends on the concentration of hydrogen sulphide. Usual levels are 2–6 % air in biogas.

The simplest method for desulphurisation is to add oxygen or air directly into the digester chamber. With this method the hydrogen sulphide level can be reduced by up to 95 % to levels lower than 50 ppm. There are of course several factors that affect the reduction rate like temperature, place and amount of air added and reaction time. When adding air into the biogas safety measures need to be taken into consideration to avoid overdosing of air in case of a pump failure. Methane is explosive in the range of 5–15 % in air.

Biological desulphurisation can also take place in a separate bio-filter filled with plastic bodies on which desulphurising micro-organisms are attached. In the unit up-flowing biogas meets a counter flow of liquid consisting of gas condensate and liquid from effluent slurry separation or a solution of minerals. Before the biogas enters the unit 5–10 % air is added. In the process the hydrogen sulphide level can be reduced from 3000–5000 ppm to 50–100 ppm. Ammonia is separated at the same time.

#### Iron chloride dosing to digester slurry

The level of hydrogen sulphide in the biogas can be reduced in the digestion chamber by adding iron chloride ( $\text{FeCl}_2$ ). The iron ( $\text{Fe}^{2+}$ ) reacts with sulphide ions ( $\text{S}^{2-}$ ) and forms iron sulphide ( $\text{FeS}$ ). At the most, the level of hydrogen sulphide is reduced to around 100 to 150 ppm depending on the amount of iron chloride added.

#### Impregnated activated carbon

Activated carbon can be used to catalytically convert hydrogen sulphide to elementary sulphur and water. As with biological desulphurisation oxygen can be added to the process. The carbon is impregnated with potassium iodide (KI) or sulphuric acid to increase the reaction rate. The sulphur containing carbon can either be regenerated or replaced with fresh carbon when it is saturated. Impregnated activated carbon is a common method for separation of hydrogen sulphide prior an upgrading system with PSA.

#### Iron hydroxide or oxide

Hydrogen sulphide reacts with iron hydroxide or oxide to form iron sulphide ( $\text{FeS}$ ). When the material is saturated it can either be regenerated or changed. In the regeneration, iron sulphide is oxidised with air and iron oxide or hydroxide is recovered together with elemental sulphur.

The iron oxide containing material can be oxidised steel wool (rust coated), wood chips covered with iron oxide or pellets made of red mud, a waste product from aluminium production. Wood chips are particularly popular in the US since they are low cost and have a large surface to volume ratio. The highest surface to volume ratio is found in pellets. Pellets are common at German and Swiss sewage treatment plants that don't have dosing of iron chloride.

#### Sodium hydroxide scrubbing

A water solution of sodium hydroxide ( $\text{NaOH}$ ) can be used to separate hydrogen sulphide. Sodium hydroxide reacts with hydrogen sulphide to form sodium sulphide or sodium hydrogen sulphide. These are both insoluble salts which means that regeneration is not possible.

#### Removal of trace gases

There are a number of trace gases in the biogas that can harm the gas distributing system or the gas utilities: Damage can be caused e.g. through corrosion, deposits or mechanical wear. Contaminants can also cause unwanted exhaust products like  $\text{SO}_x$ ,  $\text{HCl}$ ,  $\text{HF}$ , dioxins or furans.

Water, particles and if present siloxanes and halogenated hydrocarbons are components which should be removed for most of the applications either for technical reasons or to reduce maintenance cost. It is not common that the gas has to be treated to reach emissions standards.

#### Halogenated hydrocarbon removal

Halogenated hydrocarbons, particularly chloro- and fluoro-compounds are predominately found in landfill gas. The compounds cause corrosion in CHP engines and can be removed with the same methods used to remove carbon dioxide.

#### Siloxane removal

Organic silicon compounds are occasionally present in biogas from landfills and biogas from sewage sludge. Activated carbon can be used to separate organic silicon compounds from biogas. This method is very effective but it can be expensive since spent carbon can't be regenerated and needs to be replaced. This means cost for disposal as well as cost for new carbon. Another method for removing the compounds is absorption in a liquid mixture of hydrocarbons.



Vessels containing iron oxide that removes  $\text{H}_2\text{S}$  from the biogas

The level of siloxanes in biogas can also be reduced through cooling the gas and separating the condensed liquid. There are examples of systems cooling the gas to  $-25\text{ }^{\circ}\text{C}$  which result in a clean up efficiency of 26 %. The gas can be cooled even further to  $-70\text{ }^{\circ}\text{C}$  causing siloxanes to freeze, resulting in a clean up efficiency of 99 %. Cooling the gas can also be combined with an activated carbon system, giving the carbon a longer life time.

#### Removal of oxygen and nitrogen

If oxygen or nitrogen is present in the biogas this is a sign that air has been sucked into the system. This is common in landfill gas which is collected from the landfill with permeable tubes by applying a slight under pressure.

Low levels of oxygen in the gas are not a problem but high levels can pose an explosion risk. In some upgrading processes like PSA and membranes the oxygen and nitrogen content is also reduced to some extent.

#### Removal of water

Biogas is saturated with water vapour when it leaves the digestion chamber. Before biogas is used as vehicle fuel or fed into the gas grid it needs to be dried. Drying can also be necessary when using the gas for CHP, especially in gas turbines. Refrigeration is a common method for drying biogas. The gas is chilled with a heat exchanger and the condensed water is separated. In order to reach higher dew points the gas can be compressed before it is cooled.

Adsorption of water on the surface of a drying agent is a common method used to reach the very low dew points needed in vehicle fuel applications (i.e.  $-40\text{ }^{\circ}\text{C}$  or lower at 4 bar). The drying agent can be silica gel or aluminium oxide. In order to ensure continuous operation the system usually consist of two vessels one in operation and one in regeneration mode. The vessels are packed with drying agent and the moist gas is passed through the vessel. Drying can be done at elevated or atmospheric pressure. This affects the method of regeneration. When drying at elevated pressure a small stream of the dry compressed gas is depressurized and used for regeneration. If drying is carried out at atmospheric pressure, air and a vacuum pump is used for regeneration. The disadvantage with the latter method is that it results in adding some air to the biogas.

Another drying method that can be used is absorption of water in glycol or hygroscopic salts. New salt needs to be added in order to replace the saturated or even dissolved salt. The drying medium can be recovered by drying at elevated temperatures.

Biogas used as vehicle fuel needs to be dry. Water vapour can be removed by adsorption on a drying agent.

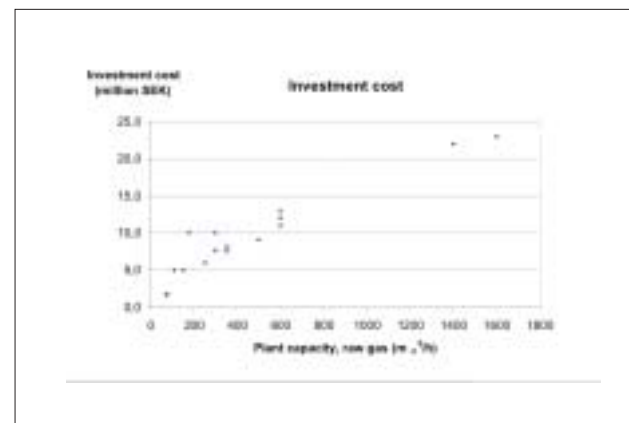


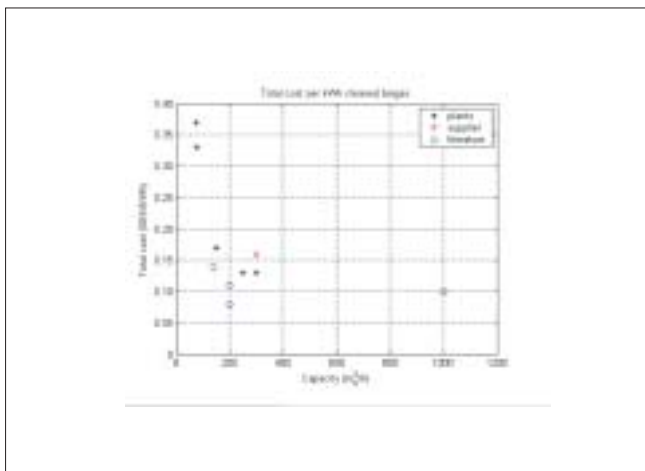
## Cost of upgrading

The total cost for cleaning and upgrading biogas derives from cost of investment as well as of operation of the plant and maintenance of the equipment. When producing biogas of vehicle fuel or pipeline quality the most expensive part of the treatment is the removal of carbon dioxide.

Investment in a plant for full treatment to vehicle fuel quality depends on several factors. One major factor is of course the size of the plant. The investment increases with increased capacity but at the same time investment per unit of installed capacity decreases for larger plants. Typical investment for a plant treating  $300\text{ nm}^3$  per hour of raw gas is in the order of 1 million Euro as shown by the graph below where investment cost for 16 upgrading plants in Sweden is listed (Swedish Gas Center, 2006). It should be pointed out that the investments in these plants have been made between 1998 and 2006. For the majority of the plants the building, where the equipment is situated, is not included in the investment cost.

The major operation costs for a plant with full treatment to vehicle fuel quality is electricity, personnel, and depending on technique, cost for consumption of i.e. water or chemicals. The plant also has cost for maintenance. Investment as well as operation and maintenance costs should be divided per kWh produced in the plant. A typical cost for an upgrading plant treating  $200\text{ nm}^3$  raw gas per hour is in the order of 1.5 €cents per kWh as shown by a Swedish study (see graph below). Cost for land at which the upgrading plant is situated is not included in the presented costs.





## Case studies

### Injection of upgraded biogas into the gas grid of Hardenberg - The Netherlands

On the landfill site "Collendoorn" in Hardenberg, located in the east of the Netherlands, landfill gas is being upgraded to natural gas quality and introduced into the gas grid. Up to now this gas has no special use (it is not earmarked and used as green gas elsewhere). The landfill and the upgrading installations are the property of Cogas, a small Dutch energy company. In 2006 around 200.000 nm<sup>3</sup> of upgraded gas were produced. It used to be over 700.000 nm<sup>3</sup>/year in the early years of the upgrading plant, but volume of gas from the landfill has decreased.

Gas upgrading is performed by membrane technology. In the first plant which was started in 1993, membranes operated with a gas pressure of 35 bar. Since 2003 a new membrane separation technology has been used enabling the gas pressure to be lowered to 9 bar. This has reduced costs and improved the economic feasibility of the plant. The upgraded gas has a methane content of 88%, a CO<sub>2</sub> content of almost 5% and an N<sub>2</sub> content of 7%. This results in a heating value and a Wobbe index of 35 and 44 MJ/nm<sup>3</sup>, respectively, which are both similar to the values of the rather low calorific

Groningen natural gas in The Netherlands. By preventing landfill gas escape to the atmosphere a CO<sub>2</sub> emission reduction of approx. 3800 tons a year is obtained (in case of 200.000 nm<sup>3</sup> upgraded gas).

### Manure and waste from food industry becomes vehicle fuel in Kristianstad - Sweden

In the town Kristianstad in the south east of Sweden biogas is produced at a co-digestion plant with a continuously stirred tank reactor. About 70.000 tonnes of waste is treated annually. About 50 % of the organic material comes from liquid manure, 45 % are waste products from the food industry and 5 % comes from household waste.

The raw biogas is transported in a 4 km long pipeline to the upgrading plant. Carbon dioxide is removed in a water scrubber without regeneration. Upgraded biogas leaving the system has a methane content of approx. 97 % as demanded by the Swedish standard. In the same upgrading plant biogas from the sewage treatment plant, located nearby, is also treated. In 2006 a second upgrading plant was put into operation. Also this plant is based on absorption of carbon dioxide in water, but this system has regeneration of the water. Two biogas plants and two upgrading facilities gives good redundancy in the system which is very important since the Swedish natural gas grid does not serve Kristianstad.

The vehicle fuel is used in cars, lorries and buses. All town buses in Kristianstad, as well as some school buses run on biogas. During 2005 1.2 million nm<sup>3</sup> of upgraded biogas was used in vehicles in the town, thus replacing an equivalent of 1.3 million litre of petrol.



Manure and waste from the food industry is digested in Kristianstad, Sweden. The biogas is used for vehicles.

## Using biogas from sewage sludge in vehicles and apartments in Stockholm - Sweden

Biogas has been produced in Stockholm, the capital of Sweden, since the beginning of 1932 mainly as a by-product from the stabilisation of municipal sewage sludge. The gas has been used for heating as well as for power production; it has also been necessary to flare biogas. About 10 years ago biogas was first used for vehicle fuel and since then production of biogas as vehicle fuel has been steadily increasing.

The municipality considers that the highest environmental benefits are gained when using biogas as vehicle fuel compared to other options. This is valid both for emissions causing environmental and health impacts (regulated and unregulated) as well as emissions with impact on the climate (primarily CO<sub>2</sub>-emissions).

Biogas produced at the two main sewage treatment plants, Henriksdal and Bromma, has a methane content of around 65 %. The Stockholm Water Company operates the plants. The final upgraded product shall contain at least 97 % methane and not more than 23 mg/nm<sup>3</sup> H<sub>2</sub>S (Swedish standard, vehicle quality, SS 155438).

The goal in Stockholm is to use all biogas from the sewage treatment for vehicle fuel and to run all (120) inner city buses on biogas. The buses are re-fuelled at a bus depot a couple of kilometres away from Henriksdal. Other vehicles can be re-fuelled at seven public biogas filling stations in the city. Five more stations are under construction/planned for the near future. Today (2006), there is a higher capacity in the upgrading plants than there is supply of raw biogas. This has initiated projects for the search of other "new" possible feedstock materials for biogas production in Stockholm.

### Henriksdals sewage treatment plant, Stockholm Water

The Henriksdal sewage treatment plant processes sewage water from the inner city and of southern parts of Stockholm, resulting in an annual production of about 9 million nm<sup>3</sup> of raw biogas.

In 2001 an upgrading plant was built. The upgraded gas is used as a vehicle fuel and for cooking and heating at an apartment complex, Hammarby Sjöstad, close to the sewage plant.

The upgrading plant is adapted for treatment of about 1400 nm<sup>3</sup> raw gas per hour, which gives a possibility to produce around 6 million nm<sup>3</sup> of upgraded biogas per year. The gas cleaning is carried out by water scrubbing with regeneration, where carbon dioxide and H<sub>2</sub>S are absorbed in water. After cleaning the water is cooled and used again while the carbon dioxide and the H<sub>2</sub>S are routed

Upgrading plant in Henriksdal, Stockholm, where the equivalent of 6 million litre of petrol can be produced annually. (Courtesy Malmberg Water)



through the ventilation system and to the chimney of the plant. Finally, an odour additive is added to the gas to make it possible to detect leaks.

The final product, the upgraded and cleaned gas, is stored at a pressure of about 350 bar. The total storage capacity is 7000 nm<sup>3</sup>. Henriksdal also has an LNG storage (liquefied natural gas) with a capacity of 66 000 nm<sup>3</sup> as a backup during maintenance or shut down in production or upgrading.

### Bromma sewage treatment plant, Stockholm Water

The Bromma sewage treatment plant produces biogas from the anaerobic digestion of municipal sewage sludge. From 1996 there has been a continuous project at the plant with the purpose of upgrading the biogas to vehicle fuel quality and to increase the upgrading capacity. Today, more or less all biogas produced is upgraded and used for vehicle fuel. During the project (erection, start-up and initial operation) there have been obstacles, but today (2006), under normal daily operation, the upgrading process runs smoothly and without any specific problems.

At the Bromma sewage plant the biogas is upgraded in two parallel gas treatment lines with a total capacity of 3.0 (2\*1.5) million nm<sup>3</sup> cleaned gas per year (600 nm<sup>3</sup> upgraded raw gas per hour). The lines have full redundancy and can be operated separately or jointly to guarantee at least half production capacity even during maintenance and operational problems.

In the upgrading process water is first removed from the biogas by condensation to a specified dew point (<-35 oC at 260 bar). The pressure of the gas is then increased to 5 bar pressure and H<sub>2</sub>S is separated in a pre-filter. Carbon dioxide is removed in the PSA (Pressure Swing Adsorption) process; The PSA plant has four separate synchronised adsorption columns that work in a cyclic mode changing between adsorption and regeneration. Finally, the gas is compressed to a pressure of 260 bar and is transferred to a storage with a total capacity of 5000 nm<sup>3</sup>.

### Marquette Sewage treatment plant, Lille - France

The Marquette sewage treatment plant was built between 1969 and 1977. Today, the plant treats about 120 000 m<sup>3</sup> sewage water per day and has two primary and two secondary digesters for sewage sludge treatment. The raw biogas from the digesters contains at least 63 % methane.

Between 1993 and 1995, a pilot biogas upgrading plant using water scrubbing was built. After start-up and optimisation of the equipment, about 80 nm<sup>3</sup> vehicle fuel could be produced per hour having a methane content of around 97 %. This was sufficient to fuel four buses.

During the first years of production there were problems reaching and keeping to the vehicle gas specification. This resulted in a need for recirculation of the product gas when it did not meet the specification. In the beginning the gas had to be recirculated several times to reach the desired specification.

Since a lot of parts were not made of stainless steel, there were also problems with

wall and piping corrosion caused by the high H<sub>2</sub>S content in the raw gas (3000 ppm). Even while these kinds of problems were experienced, it was still possible to run the upgrading plant for almost 9 years but, by 2004 corrosion had deteriorated the upgrading equipment to such an extent that it was not safe to operate it further and the operation of the facility was eventually stopped.

However, in 2006 the decision was taken to construct a new upgrading facility at the Marquette plant and at this time, not a pilot plant but a reliable industrial installation. The original principle of cogeneration will probably be retained and even if the biogas is primarily used for electricity and heating purposes, the capacity of upgraded biogas for vehicle purposes will be increased to such an extent that at least ten buses can be fuelled.

#### Grid injection of upgraded biogas from OFMSW - Jona, Switzerland

In spring 2005 a small scale digestion plant for the treatment of 5.000 tpy of source separated organic waste (OFMSW) has started operation in Engelhölzli, Jona. It is a solid waste digester operated at thermophilic temperatures (55 to 57°C). The retention time in the digester is about 15 days. The digestate is mixed with garden waste and post-composted in an enclosed hall.

The gas is upgraded with a new Genosorb washing system. The hydrogen sulphide as well as the humidity is preliminary removed by activated carbon.

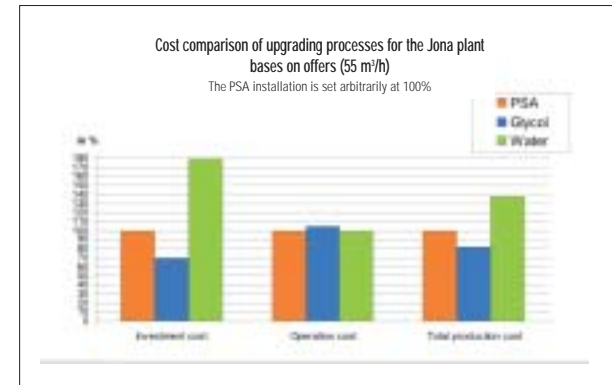
It is the first plant in Switzerland without an additional CHP. The entire gas production is upgraded without intermediate storage and is fed to the natural gas grid. Process electricity is taken from the power line, process heat is produced with a natural gas boiler.

Another novelty of the plant is the ownership. In all previous plants in Switzerland the owner of the digestion unit was also the owner of the upgrading plant. He delivered the clean and odorised gas to the grid. In Jona on the other hand he sells the raw gas to the gas company. They own and operate the upgrading plant themselves.

The design capacity of the upgrading plant is 55m<sup>3</sup> of raw gas per hour. With an input to the digester of about 20 tons of fresh waste per working day, the gas production is often far higher than the treatment capacity. Hence, some of the gas has to be flared. Actually, the plant capacity is increased.

The system has been selected because it had the lowest production cost with 2.2 €cents per kWh when compared to PSA and water washing on the basis of offers.

Upgrading plant in Jona with a washing and a regeneration tower operated on Genosorb



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| COUNTRY     | CITY                     | PRODUCTION GAS UTILISATION gas grid or vehicle fuel | BIOGAS PRODUCTION (landfill gas/sew.sludge/waste/manure) | CH4 REQUIREMENTS % | CO2 REMOVAL TECHNIQUE | H2S REMOVAL TECHNIQUE | PLANT CAPACITY RAW GAS | IN OPERATION SINCE |
|-------------|--------------------------|---|--|--------------------|-----------------------|-----------------------|------------------------|--------------------|
| Austria     | Pucking                  | Gas grid  | Manure   | 97                 | PSA                   | Biol. filter          | 10                     | 2005               |
| Canada      | Berthierville (Quebec)   | Gas grid  | Landfill gas   |                    | Membrane              | Activated carbon      |                        | 2003               |
| France      | Lille                    | Vehicle fuel  | Sewage sludge  |                    | Water scrubber        | Water scrubber        | 100                    | 1993               |
|             | Lille                    | Vehicle fuel  | Biowaste, manure   | 97                 | Water scrubber        | Water scrubber        | 2 x 600                | 2007               |
| Germany     | Jameln                   | Vehicle fuel  | Manure, energy crops                                     | 96                 | Selexol scrubbing     | Selexol scrubbing     | 100                    | 2006               |
|             | Kerpen                   | Gas grid  | Energy crops   |                    | PSA                   | Activated carbon      | 500                    | 2006               |
|             | Pliening                 | Gas grid  | Energy crops   |                    | PSA                   | Activated carbon      |                        | 2006               |
|             | Straelen                 | Gas grid  | Energy crops, manure                                     |                    | PSA                   | Activated carbon      |                        | 2006               |
|             | Rathenow                 | Gas grid  | Energy crops, manure                                     |                    | PSA                   | Activated carbon      | 500                    | 2006/2007          |
| Iceland     | Reykjavik                | Vehicle fuel  | Landfill gas   | -                  | Water scrubbing       | Water scrubbing       | 700                    | 2005               |
| Japan       | Kobe                     | Vehicle fuel  | Sewage sludge  | 97                 | Water Scrubbing       | Water scrub           | 100                    | 2004               |
|             | Kobe                     | Vehicle fuel  | Sewage sludge  | 97                 | Water scrubbing       | Water scrub           | 2 x 300                | 2007               |
| Netherlands | Collendoorn (Hardenberg) | Gas grid  | Landfill gas   | 88                 | Membrane              | Activated carbon      | 375                    | 1991               |
|             | Nuenen                   | Gas grid  | Landfill gas   | 88                 | PSA                   | Activated carbon      | 1500                   | 1990               |
|             | Tilburg (Spinder)        | Gas grid  | Landfill gas   | 88                 | Water scrubber        | Iron oxide pellets    | 2100                   | 1987               |
|             | Wijster                  | Gas grid  | Landfill gas   | 88                 | PSA                   | Activated carbon      | 1150                   | 1989               |
| Norway      | Fredrikstad              | Vehicle fuel  | Sew.sludge/waste   | 95 ± 2             | PSA                   | -                     | 150                    | 2001               |
| Spain       | Vacarisses (Barcelona)   | Vehicle fuel  | Landfill gas   | > 85               | Chemical absorption   | Activated carbon      | 100                    | 2005               |
|             | Madrid                   | Vehicle fuel  |  | 96,5               | Water Scrubbing       | Water scrubbing       | 4000                   | 2007               |
| Sweden      | Borås                    | Vehicle fuel  | Biowaste household and industry Sewage sludge            | 97                 | Chemical absorption   | Activated carbon      | 300                    | 2002               |
|             | Goteborg                 | Gas grid  | Sewage sludge  | 97                 | Chemical absorption   | Activated carbon      | 1600                   | 2006               |
|             | Helsingborg              | Vehicle fuel and gas grid                           | Biowaste household and industry manure                   | 97                 | PSA                   | Activated carbon      | 350                    | 2002               |
|             | Stockholm                | Vehicle fuel  | Sewage sludge  | 97                 | PSA                   | Activated carbon      | 600                    | 2000               |
|             | Stockholm                | Vehicle fuel  | Sewage sludge  | 97                 | Water scrubber        | Water scrubber        | 600<br>800             | 2003<br>2006       |
|             | Skövde                   | Vehicle fuel  | Sewage sludge, slaughter waste                           | 97                 | PSA                   |                       | 110                    | 2003               |
|             | Uppsala                  | Vehicle fuel  | Waste from food industry, manure, sewage sludge          | 97                 | Water scrubber        | Water scrubber        | 200<br>400             | 1997<br>2002       |
|             | Trollhattan              | Vehicle fuel  | Sewage sludge, organic household waste                   | 97                 | Water scrubber        | Water scrubber        | 140<br>400             | 1996<br>2001       |

| COUNTRY     | CITY                         | PRODUCTION GAS UTILISATION gas grid or vehicle fuel | BIOGAS PRODUCTION (landfill gas/sew.sludge/waste/manure) | CH4 REQUIREMENTS % | CO2 REMOVAL TECHNIQUE | H2S REMOVAL TECHNIQUE | PLANT CAPACITY RAW GAS | IN OPERATION SINCE |
|-------------|------------------------------|---|--|--------------------|-----------------------|-----------------------|------------------------|--------------------|
|             | Norrköping                   | Vehicle fuel  | Sewage sludge  | 97                 | Water scrubber        | Water scrubber        | 275                    | 2004               |
|             | Norrköping                   | Vehicle fuel  | Residue from ethanol production, energy crops            | 97                 | Water scrubber        | Water scrubber        | 240                    | 2006               |
|             | Eskilstuna                   | Vehicle fuel  | Sewage sludge  | 97                 | Water scrubber        | Water scrubber        | 330                    | 2003               |
|             | Jönköping                    | Vehicle fuel  | Sewage sludge, biowaste industry                         | 97                 | Water scrubber        | Water scrubber        | 150                    | 2000               |
|             | Västerås                     | Vehicle fuel  | Biowaste household and pasture Sewage sludge             | 97                 | Water scrubber        | Water scrubber        | 480                    | 2004               |
|             | Kristianstad                 | Vehicle fuel  | Biowaste household and industry manure Sewage sludge     | 97                 | Water scrubber        | Water scrubber        | 300<br>600             | 1999<br>2006       |
|             | Linköping                    | Vehicle fuel  | Biowaste household and industry manure Sewage sludge     | 97                 | Water scrubber        | Water scrubber        | 660<br>1400            | 1997<br>2002       |
| Switzerland | Bachenbülach                 | Gas grid  | Biowaste   | 96                 | PSA                   | Activated carbon      | 200                    | 1996               |
|             | Jona                         | Gas grid  | Biowaste   | 96                 | Genosorb washing      | Activated carbon      | 55                     | 2005               |
|             | Lucerne                      | Gas grid  | Sewage sludge  | 96                 | PSA                   | Activated carbon      | 75                     | 2004               |
|             | Oteltingen                   | Vehicle fuel  | Biowaste   | 96                 | PSA                   | Activated carbon      | 50                     | 1998               |
|             | Pratteln                     | Gas grid  | Biowaste   | 96                 | Genosorb washing      | Activated carbon      | 300                    | 2006               |
|             | Rümlang                      | Vehicle fuel  | Biowaste   | 96                 | PSA                   | Activated carbon      | 30                     | 1995               |
|             | Samstagern                   | Gas grid  | Biowaste   | 96                 | PSA                   | Activated carbon      | 50                     | 1998               |
| USA         | Los Angeles, (CA)            | Vehicle fuel  | Landfill gas   | 96                 | Membrane              | Activated carbon      | 2600                   | 1993               |
|             | Houston (TX)                 | Gas grid  | Landfill gas   |                    | Selexol scrubbing     | Selexol scrubbing     | 9 400                  | 1986               |
|             | Staten Island, (NY)          | Gas grid  | Landfill gas   |                    | Selexol scrubbing     | Iron oxide wood chips | 13 000                 | 1981               |
|             | Cincinnati (OH)              | Gas grid  | Landfill gas   |                    | PSA                   |                       | 10 000                 | 1986               |
|             | Dallas (TX)                  | Gas grid  | Landfill gas   |                    | PSA                   |                       | 10 000                 | 2000               |
|             | Pittsburg - Valley (PA)      | Gas grid  | Landfill gas   |                    | Membrane              |                       | 5 600                  | 2004               |
|             | Pittsburg - Monroeville (PA) | Gas grid  | Landfill gas   |                    | Membrane              |                       | 5 600                  | 2004               |
|             | Shawnee (KS)                 | Gas grid  | Landfill gas   |                    | Physical absorption   |                       | 5 500                  | 2001               |
|             | Dayton (OH)                  | Gas grid  | Landfill gas   |                    | Krysol (methanol)     |                       | 6 000                  | 2003               |
|             | Renton (WA)                  | Gas grid  | Sewage sludge  | 98                 | Water scrubber        | Water scrubber        | 4000                   | 1984 + 1998        |

## SOME ABBREVIATIONS AND DEFINITIONS

|                         |  |
|-------------------------|--|
| AD, anaerobic digestion | Microbiological degradation of organic material in the absence of oxygen.  |
| CHP                     | Combined heat and power.   |
| CNG                     | Compressed natural gas.  |
| Gas relative humidity   | Ratio of the amount of water vapour in the gas to the maximum amount of water vapour that could be in the gas if the vapour were at its saturation conditions.   |
| H gas                   | Natural gas with high heating value.   |
| Heating value           | Amount of energy released when a fuel is burned completely. Higher heating value includes recovered heat from condensing water vapour that is produced in the combustion. Also called calorific value. |
| L gas                   | Natural gas with low heating value.  |
| nm <sup>3</sup>         | normal cubic meter Volume at atmospheric pressure (1.01325 bar) and 0°C, also called STP (standard pressure and temperature).  |
| MSW                     | Municipal solid waste  |
| PSA                     | Pressure Swing Adsorption. Technique for separation of carbon dioxide.   |
| Wobbe index             | Heating value divided by the square root of the gas relative density to air.   |

