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Overview of Biogas Technology

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WP6 Energy potentials

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OVERVIEW OF BIOGAS TECHNOLOGY

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PREFACE

This report is an overview of biogas technologies with the aim of introducing them in a simple, easy-to-read way. More detailed information will also be available at the MANURE KNOWLEDGE FORUM of the project Baltic MANURE (http://www.balticmanure.eu). The authors also recommend the recent report "Best available technologies for pig manure biogas plants in the Baltic Sea Region" for more in-depth information (available at http://www.balticsea2020.org).

In this report, Argo Normak (Estonian University of Life Sciences) was mostly responsible for chapters 4.1 and 4.2, while Mats Edström (Swedish Institute of Agricultural and Environmental Engineering, JTI) for chapter 5. Sari Luostarinen (WP leader, MTT Agrifood Research Finland) wrote the remaining chapters and edited the report into its final form.

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the authors

CONTENT

1   Introduction

Interest in biogas technology is increasing around the world due to the requirements for renewable energy production, reuse of materials and reduction of harmful emissions. Biogas technology offers versatile and case-specific options for tackling all of the above mentioned targets with simultaneous controlled treatment of various organic materials (see chapter 2). It produces methane-rich biogas which can be utilised as renewable energy in various ways (see chapter 5). The residual material, digestate, contains all the nutrients of the original raw materials and offers a way to recycle them (see chapters 4.4 and 6). Along the process steps, also emissions directly from the raw materials (storage, use, disposal) or from the replaced products (fossil fuels, inorganic fertilisers) can be reduced (as pointed out throughout the report).

Biogas technology is currently the most sustainable way to utilise the energy content of manure while also recycling the nutrients and minimising the emissions. In this report, special emphasis is given to the anaerobic digestion of manure, alone and with co-substrates.

2   Principles of biogas technology

Biogas technology, i.e. anaerobic digestion is biological method for degrading and stabilising organic, biodegradable raw materials in special plants in a controlled manner. It is based on microbial activity in oxygen-free (anaerobic) conditions and results in two end-products: energy-rich biogas and nutrient-rich digestion residue, i.e. digestate. Anaerobic degradation of biodegradable materials also happens in nature, e.g. in swamps, soils, sediments and in ruminant metabolism.

2.1.1   _Anaerobic degradation_

During the anaerobic degradation process several different microbial consortia degrade the raw materials in parallel and/or subsequent degradation steps (Figure 1).
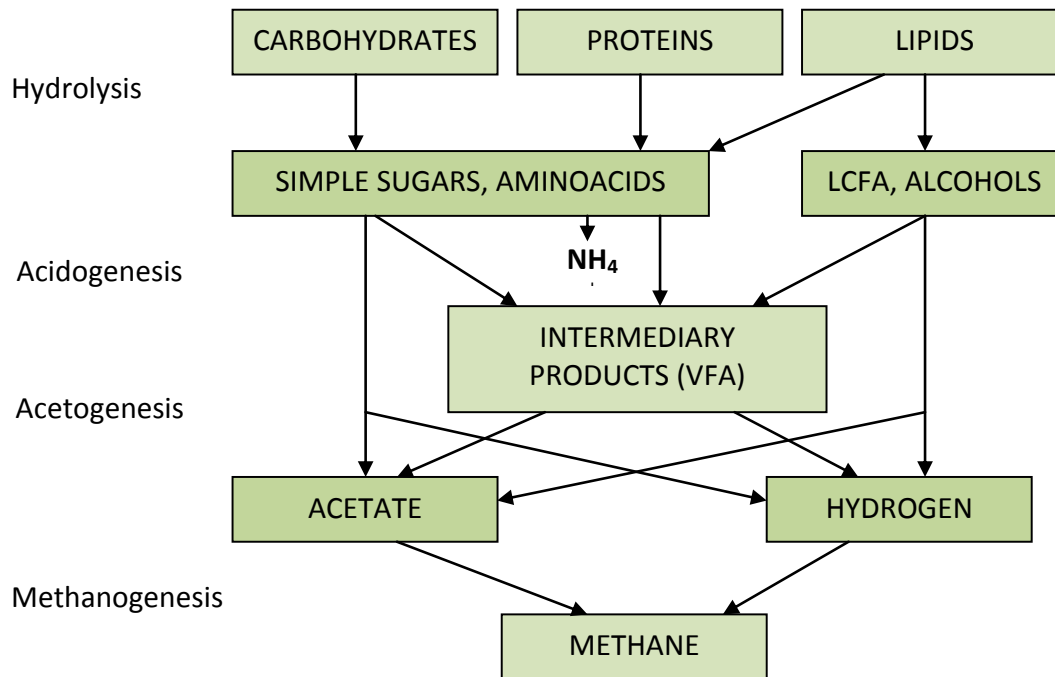
Hydrolysis

| CARBOHYDRATES | PROTEINS | LIPIDS |

| SIMPLE SUGARS, AMINOACIDS | LCFA, ALCOHOLS |

Acidogenesis

NH_4

INTERMEDIARY PRODUCTS (VFA)

Acetogenesis

| ACETATE | HYDROGEN |

Methanogenesis

METHANE

Figure 1. Anaerobic degradation of organic, biodegradable material (simplified after Gujer & Zehnder, 1983).

In hydrolysis, the polymers (carbohydrates, proteins and lipids) are degraded into their monomers and dimers via hydrolytic enzymes excreted by acidogenic microbes. The higher the surface area of the raw materials, the more efficiently the hydrolytic enzymes can attack the material (Sanders et al., 2000). Therefore, hydrolysis is often the rate-limiting step in the degradation of particulate raw materials (.e. materials containing solids; Mata-Alvarez, 2003) and pre-treatments, such as maceration, may be used in order to improve it (see chapter 4.3). Also, the process operational conditions affect hydrolysis, e.g. higher temperature enhances hydrolysis. Optimal pH is approximately 6.0, though hydrolysis occurs also at higher pH (Sleat & Mah, 1987). Too high organic loading rate (OLR) may inhibit hydrolysis through accumulation of degradation intermediates (Pavlostathis & Giraldo-Gomez, 1991; Sanders, 2001).

Once the raw materials are degraded into smaller molecules, i.e. long chain fatty acids (LCFA), alcohols, simple sugars and amino acids, during hydrolysis, the acidogenic bacteria are able to uptake them and facilitate further degradation into volatile fatty acids (VFA) (Pavlostathis & Giraldo-Gomez, 1991; Mata-Alvarez, 2003; Gerardi, 2003). The more specific intermediate products (e.g. priopionic, butyric and valeric acid) depend on operational conditions, raw materials and microbial activity. One part of acidogenesis is also ammonification of nitrogen compounds into ammonium-nitrogen (NH_4^+-N), a noteworthy compound due to possible toxicity (see chapter 2.2) and to the increased fertiliser value of the digestate (see chapter 7).

Acetogenesis then facilitates degradation of the intermediate VFAs into acetate, hydrogen and carbon dioxide (Mata-Alvarez, 2003). These are the compounds the methane-producing microbes (methanogens) are able to utilise in their metabolism and convert them into biogas, a mixture of methane and carbon dioxide (+ small quantities of other gaseous compounds; see chapter 5).

Approximately 70% of methane is usually produced from acetate (acetoclastic methanogens) and 30% from hydrogen and carbon dioxide (hydrogenotrophic methanogens; Oremland, 1988, Gerardi, 2003).

2.2 Factors affecting anaerobic degradation

There are several factors which may affect the anaerobic degradation of biodegradable materials. In this chapter, the most important ones are described shortly.

2.2.1 Temperature and pH

Temperature influences the growth and survival of the micro-organisms. The lower the temperature, the slower the chemical and enzymatic reactions and microbial growth are. As the temperature rises, the chemical and enzymatic reactions are accelerated, but only up to certain temperature optima. If this optimum is exceeded, proteins and cellular components of the microbes may be irreversibly damaged. Thus, increasing temperature within one optimum may enhance anaerobic degradation, but become damaging to that particular microbial consortium at temperatures higher than the optimum (Madigan et al., 1997).

Microbes are classified into different temperature classes according to their temperature optima and these same optima are then used in biogas plant operation. Psychrophilic and psychrotolerant microbes grow at temperatures from 0-20 °C (Madigan et al., 1997). Biogas plants operating at these low temperatures usually treat wastewaters with high amounts of soluble organic compounds, such as distillery wastewater. Mesophilic microbes have their temperature optimum at 30-40 °C and thermophilic at over 55 °C (Madigan et al., 1997). Meso- and thermophilic processes are the most common when digesting heterogeneous raw materials, such as manure, sewage sludge and different biodegradable wastes and by-products from municipalities and industry (see chapters 3 & 4). In a biogas plant, the digester (reactor) has to be heated in order to keep it at the temperature desired. Thus, the biogas plant uses part of the energy it produces into its own heating.

Temperature is also important for chemical equilibria in a biogas process (e.g. gas solubility, precipitation stage of inorganic materials) and links therein with pH. Optimal pH for hydrolysing enzymes is 6.0 (Sleat & Mah, 1987), but that for methanogenesis is 6.0-8.0 (Oremland et al., 1988). pH affects the degradation directly through the microbes but also indirectly via the chemical equilibria of possible ammonia and VFA toxicity (see below), availability of nutrients and raw materials (e.g. precipitation of proteins) and availability of carbon dioxide. In order to maintain the pH desired within a biogas process, sufficient alkalinity, i.e. buffering capacity is required. Many raw materials for biogas processes have high alkalinity, but it can also be increased by addition of e.g. bicarbonates, if required.

2.2.2 Inhibition and hydrogen partial pressure

Ammonification of organic nitrogen compounds produces ammonium nitrogen, part of which is present as its unionised form of ammonia (NH_3). As ammonia is able to enter microbial cells rather freely due to having no electrical charge, it becomes toxic for the microbes at high concentrations. The amount of ammonia depends on the temperature and pH of the process, i.e. the higher the

temperature and the pH, the higher the amount of ammonia. The microbial consortia in a biogas process are able to adapt to higher nitrogen concentrations. Still, it is advisable to perform the increase step-by-step, allow the process time for adaption and thus recognise, when the highest possible nitrogen content in the feed is reached (Angelidaki & Ahring, 1993; Hansen et al., 1998, Mata-Alvarez, 2003).

A sufficiently low partial pressure of hydrogen is vital for well-functioning biogas processes, and especially acidogenesis, acetogenesis and subsequently methanogenesis depend on it. The degradation or accumulation of intermediate products, LCFA and VFA, and their possible inhibitive functions, are also linked to it (McInerney, 1988; Pavlostathis & Giraldo-Gomez, 1991; Mata-Alvarez, 2003). The degradation of LCFA and VFA is thermodynamically infavourable when the hydrogen partial pressure is high. Usually the hydrogenotrophic methanogens immediately consume the hydrogen produced, but in cases of organic overload (too high amount of feed) or other inhibitive conditions for methanogens, the degradation of these organic acids is impaired, acid content increases and pH decreases. This further inhibits the methanogens and results in increased hydrogen partial pressure. At this point also the degradation of LCFA and VFA to acetate does not proceed and other intermediate products (e.g. propionate and other longer-chained VFA) are produced in excess, causing acidification of the biogas process. This may result in a complete deterioration of the process and can be overcome only over a long period of no feeding or re-start of the whole process using new inoculum.

Other possible inhibitors for a biogas process are e.g. oxygen, disinfective compounds, high concentrations of heavy metals, nitrate, suphate, 2-bromoethanesulphonic acid (BES), chlorinated methanes and compounds with unsaturated carbon-carbon bonds, such as acetylene (Oremland, 1988).

2.2.3 *Technical and operational factors*

Also technical and operational factors affect anaerobic degradation in biogas processes. For instance, mixing is important in all digester types (see 3-4). It is used to ensure good contact between the raw materials and the microbes, as well as constant temperature and homogenous quality throughout the digester contents. It also enables release of the biogas bubbles from the digested mass into the gas collection system. Suboptimal mixing may result in low-quality (unstabilised) digestate, reduce biogas production and result in operational problems, such as foaming, pockets of unreleased biogas within the digested mass and/or mass rise and penetration into wrong outlets. Mixing is often enabled by differently shaped and placed blade mixers, though gas mixing, i.e. releasing biogas into the digester contents via nozzles is also used (Hobson & Wheatley, 1991). Mixing should be optimised also for energy reasons as it is often the main electricity consumer in a biogas plant.

Also the hydraulic retention time (HRT) and OLR affect biogas processes. HRT is the relation of reactor volume and the volume of daily feed and represents the average time the raw materials spend in the biogas process. The longer the HRT, the more of the organic matter (VS) is degraded. Still, the organic matter most prone to anaerobic degradation is usually degraded within 14-50 days (in biogas reactor only), depending on the raw materials, and higher HRTs merely require larger reactor volumes with little benefits. In case of easily degraded materials, such as starch

containing vegetable residues, a short HRT is sufficient, while lignocellulosic materials, such as energy crops and crop residues, require longer HRT to facilitate efficient degradation. When digesting manure, 20-30 days is a usual HRT applied.

OLR describes the quantity of organic matter to be treated in a specific process at a given time and is interconnected to HRT (OLR = the amount of organic material (VS) in daily feed divided by the reactor volume). All biogas processes have a threshold OLR above which OLR cannot be increased due to either technical limitations (too high TS for the plant design results in e.g. inefficient mixing and blockages) or microbiological limitations (too much VS in feed resulting in intermediate inhibition).

3   Raw materials for biogas processes

Different raw materials will produce different amounts of biogas and methane depending on their content of carbohydrates, fats and proteins (Table 1; Buswell & Neave, 1930). In theory, all biodegradable materials with reasonable lignin content (i.e. not wood) are suitable raw materials for biogas processes. In agriculture, manure and most plant biomass can be directed to biogas plants, while from municipalities, food waste and sewage sludge are the most important material flows to biogas processes. Moreover, different industries produce biodegradable by-products which can be used in biogas plants.

Table 1. Theoretical biogas and methane production from carbohydrates, fats and proteins (Buswell & Neave, 1930).

Substrate	Biogas (m^3/t)	Methane (m^3/t)	Methane content (%)
Carbohydrates	830	415	50,0
Fats	1444	1014	70,2
Proteins	793	504	63,6

3.1.1   *Manure*

Basically all manures can be directed to biogas plants, but depending on their quantities and characteristics and the plant design they can be either digested alone or in conjunction to digestion of other raw materials (co-digestion, see below). The methane production potential of manures differs between the manure types (Table 2) and also case-specifically depending on e.g. animal feeding and housing solutions, manure TS content and the bedding material used. Manure is a good base material for biogas plants as i) it is continuously produced and available, ii) it contains all the nutrients required by the anaerobic bacteria, and iii) has high buffering capacity. Still, the nitrogen content of especially poultry manure may require specific technologies (e.g. dilution with fresh or purified process water or co-digestion with other, less nitrogen-rich materials) in order to avoid inhibition.

TABLE 2. Average characteristics of different manures and their biological methane potentials (BMP).

Manure	TS (%)	VS (% of TS)	Ntot (% of TS)	BMP (m^3/tVS added)	BMP (m^3/tFM added)	Ref.
Cow, liquid	5-14	75-85	3-6	120-300	10-20	1-5
Cow, solid	17-25	68-85	1.1-3.4	126-250	24-55	1-5
Pig, liquid	4-10	75-86	6-18	180-490	12-24	1-5
Pig, solid	20-34	75-81	2.4-5.2	162-270	33-39	1-5
Poultry, solid	32-65	63-80	3.1-5.4	150-300	42-156	1, 3-6

Reference: 1) Viljavuuspalvelu, 2004; 2) Steineck et al., 1999; 3) KTBL, 2010; 4) Ministerium für Ernährung, Landwirtschaft, Forsten und Fischerei Mecklenburg-Vorpommern, 2004; 5) Institut für Energetik und Umwelt et al., 2006; 6) Edström, 2011.

3.1.2 *Energy crops and crop residues*

For biogas production, plant biomass, i.e. energy crops and/or crop residues, should be harvested within their growing period as fresh, green plants. The more dry and straw-like the plant, the less biogas it produces (e.g. Lehtomäki, 2006; Amon et al., 2007; Seppälä et al., 2009). Plant biomass can be fed to biogas reactors freshly cut or after storage. In suboptimal storing conditions, the crops may be partly degraded which usually decreases their BMP. Thus, storage should be optimised for preventing such degradation. Ensiling and paling are advisable storing methods for most crop materials. Ensiling e.g. maize under optimal anoxic conditions and no additives has been reported to even increase BMP by 25%, apparently due to formation of organic acids (lactic acid) which serves as a precursor for methane production (Amon et al., 2007). The examples of crop BMPs and methane yields during continuous co-digestion with manure (Table 3) illustrate the significant energy potential of crop materials as compared to digesting manure alone (Table 3). Even small addition of crops increases the methane yield significantly.

TABLE 3. BMPs of different energy crops and crop residues and methane yield in full-scale co-digestion with manure.

Substrate	Ratio of manure:crop (w.w.)	HRT (d)	OLR (kgVS/ m^3d)	BMP/CH_4 (m^3/tVS added)	BMP/CH_4 (m^3/tFM added)	Ref.
Maize	nd	nd	nd	410	nd	1
Maize	nd	nd	nd	312-365	nd	2
Wheat	nd	nd	nd	390	nd	1
Barley	nd	nd	nd	360	nd	1
Grass	nd	nd	nd	410	nd	1
Grass (timothy-clover)	nd	nd	nd	370-380	72-85	3
Grass silage	nd	nd	nd	306-372	72-104	3
Reed canary grass	nd	nd	nd	253-351	47-116	4
Clover	nd	nd	nd	350	nd	1
Red clover	nd	nd	nd	280-300	41-68	3
Cow manure + grass silage	93:7	54	2.7	240	17	5
Pig manure + rye + maize	43-50:50-57	75-130	2.11-4.25	360-400	nd	6

nd = not determined
Reference: 1) Weiland, 2003; 2) Amon et al., 2007; 3) Lehtomäki, 2006; 4) Seppälä et al., 2009; 5) Luostarinen, 2011; 6) Lindorfer et al., 2008.

3.1.3 *Municipal and industrial materials*

Several municipal and industrial wastes and by-products are suitable substrates for biogas plants Table 4). The characteristics of these materials may vary in many ways. For example, the characteristics of the organic fraction of municipal solid waste (OFMSW) vary depending on collection method (source-or mechanically sorted), collection site (restaurant, school, hospital, residential area etc.) and time of year (e.g. amount of gardening waste; Ward et al., 2008). Also, sewage sludge from municipal and industrial wastewater treatment plants may be directed to biogas processes. Its characteristics are also variable depending on the wastewater treatment process and the wastewater origin. Many by-products from food-processing offer good raw materials for biogas plants, but other organic, industrial raw materials are also available.

TABLE 4. BMPs of some municipal and industrial wastes and by-products.

Substrate	BMP (m³/tVS added)	BMP (m³/tFM added)	Ref.
OFMSW, food waste	300-500	130	1-2
Sewage sludge	220-430	10-32	1-4
Meat-processing by-products	500-900	100-300	5
Grease trap sludge	920	250	1
Potato by-products	323-373	nd	6

nd = not determined; OFMSW = organic fraction of municipal solid waste
Reference: 1) Luostarinen ym. 2008; 2) Davidsson ym. 2007; 3) Einola ym. 2001; 4) Järvinen & Rintala 1996; 5) Salminen & Rintala 2002; 6) Kryvoruchko et al., 2009.

3.1.4 *Co-digestion*

Co-digestion of two or more raw materials may be done in order to i) increase biogas production, ii) overcome inhibition by dilution with co-substrates, iii) increase profitability via gate fees for receiving and treating raw materials from third parties, and iv) improve degradation via synergies produced by mixing different materials (Mata-Alvarez et al., 2000). Co-digestion may, however, affect the process requirements through legislation. E.g. EU ABP regulation applies to biogas plants digesting materials of animal-origin, including food waste from restaurants, shops and cafeterias. If e.g. manure is to be digested with food waste, hygienisation (see chapter 4.3) is required. Also national legislation may contain process requirements also for the digestate use intended. E.g. in Finland, if the digestate from a farm-scale or farm-cooperative biogas plant is to be sold or handed over to third parties (i.e. other than the farmer or the partners in the cooperative), hygienisation may be required depending on the raw materials used, while the hygienisation is not compulsory, when the farmer or partners in the cooperative use the digestate themselves. The farmers, intending to use the digestate on their own fields, should also pay attention to the nutrients contained in the co-substrates. The farm(s) should have sufficient field area for the application of also these 'new' nutrients, additional to those already contained in their manure. Larger biogas plants intending to post-process the digestate into marketable fertiliser products have no such problems, but rather prefer receiving more nutrients.

4 Technological and operational solutions for biogas plants

Biogas plants are always case-specific. They are designed according to those particular conditions and characteristics and quantities of raw materials as intended when commissioning a plant. There are several technological and operational solutions to choose from and the length of the technology chain applied differ from smaller to larger scale according to factors, such as investment and operational cost, workload, the end-use of digestate intended, goals for energy production etc. In small household plants very simple technological solutions are used. On farm-scale the technology becomes somewhat more elaborate, but the aim is to still keep it simple and easy-to-use, while on large, centralised scale the biogas plant may consist of several different processing units the operation of which requires more monitoring and knowhow.

4.1 Different scales

Biogas is produced in biogas plants which differ in size (scale) and technology. Small and often self-made biogas plants are used in tropical countries for treating wastes from the household farming and cooking. In industrial countries with intensive agriculture the biogas plants are significantly bigger and more advanced, equipped with modern technology to increase digester capacity and to apply process control for stable operation. Generally agricultural biogas digesters can be divided into different scales by size:

- Small household digesters
- Agricultural biogas plants: farm-scale, farm cooperative
- Centralised biogas plants

4.1.1 Household digesters

Household digesters are very simple and manually operated (Fig. 2). This type of biogas plants can be effectively operated under warm climate conditions, while implementation in temperate to cold areas may require temperature control. The biogas produced is usually utilised for cooking and lighting. For example in China, there were 26.5 million biogas plants in 2007, most of them household digesters of 6-10 m^3.
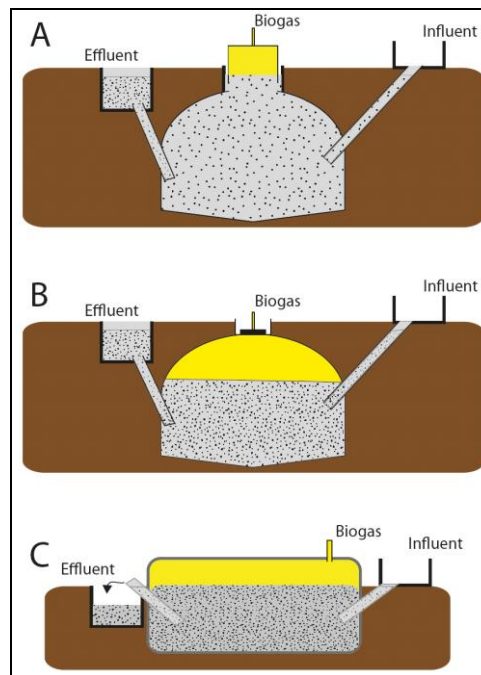
Figure 2. Household biogas plants: A Floating-drum plant, B Fixed-dome plant, C Balloon plant (Sasse, 1988).

4.1.2 *Agricultural biogas plants*

Agricultural biogas plants are integrated with animal husbandry and/or crop production, with manure and herbal biomass as the usual raw materials. Farm-scale biogas plants have robust, simplified technology and basic automation to maintain a stable process, while larger biogas plants for farm cooperatives may also use more advanced and complex technologies. In a German biogas handbook, agricultural biogas plants are divided into three groups by electrical capacity of CHP unit (Institut für Energetik und Umwelt et al., 2006):

- Small scale ≤ 70 kW
- Medium scale 70–150 kW
- Large scale 150–500 kW

According to this division, the small to medium scale would be applicable on single farms, while medium to large scale would most likely be of farm cooperatives.

Farm-scale plants usually aim at closing the energy and nutrient cycles in the farm and offer a good basis for sustainable energy supply. General scheme of a farm-scale biogas plant is presented in Figure x, with co-digestion of manure and energy crops in a simple anaerobic reactor. The main products of the biogas plant in Figure 3 are electricity, heat and digestate. Depending on the local requirements and pricing situation for the energy, the energy produced is either used on farm to replace energy from grid or sold to the grid (electricity, heating). Possibly other practices, such as biogas upgrading to biomethane for fuel, reuse of fibers from manure for bedding and use of irrigation as a means of applying mechanically separated liquid fraction of digestate on fields, can be applied (Philip, 2005).

Farm cooperative biogas plants usually focus on closing nutrient cycles on the cooperating farms with possible re-division of the manure nutrients, i.e. farms with excess phosphorus may receive less phosphorus in digestate than they deliver the plant in the raw manure, while farms with phosphorus requirement receive more phosphorus in digestate than they deliver to the plant. Also in addition to animal farms, some farms in the cooperative may be crop producers, providing the plant with some crops and receiving digestate. For example in Germany, many agricultural biogas plants use energy crops with less or no manure and use the digestate for the crop production. The energy produced in farm cooperative biogas plants is usually sold to the grid (electricity grid and/or heating networks) or utilised in adjacent companies, such as greenhouses. Biogas upgrading to biomethane is also possible.

A few examples of existing agricultural biogas plants are also described in the separate Baltic MANURE report "Examples of existing good practices in manure energy use" (available at http://www.balticmanure.eu).

Figure 3. General scheme of a common biogas plant with continuously stirred tank reactor (CSTR) in Europe (Institut für Energetik und Umwelt et al., 2006).

4.1.3   Centralised biogas plants

In centralised biogas plants, the technological solutions are usually more complex than in biogas plants focusing on agricultural materials of one or a few farms. Moreover, the raw materials are often collected from several sources and the feed mixture may contain diverse materials from agriculture, municipalities and industry. The choice of technology varies case-specifically depending on the raw materials available, the aims of the processing (e.g. energy production,

fertiliser production, stabilisation of waste materials, reduction of environmental load), the costs for investment and operation, subsidy systems available, etc. For example in Denmark, there are many large, centralised biogas plants only for digestion of liquid manure, a development active in the 1980s and since directed towards smaller farm-scale plants (Seadi, 2000; Raven & Gregersen, 2007). On the contrary in Finland, centralised biogas plants digest diverse raw materials from agricultural materials to those from the municipalities and industry. Also during the last years, centralised biogas plants have been built in Germany e.g. with one of the biggest biogas parks by NAWARO BioEnergie AG in Penkun. The Penkun biogas park has 40 modules of 500 kW electrical power each, digesting mainly energy crops. The thermal energy produced is used in a fertilizer factory next to the biogas park (EnviTec Biogas AG Newsletter, 2011).

Centralised biogas plants may produce heat or heat and power depending on the case-specific conditions, but the economy of scale may also make biomethane production more attractive than in smaller biogas plants (see: chapter xx). E.g. a biogas park in Güstrow, Germany (Figure 4) upgrades biogas to natural gas standards and the biogas production is equal to a thermal output of 55 MW. Other examples of biomethane production in existing biogas plants (centralised: Katrineholm, Sweden; farm-scale: Kalmari Farm, Finland) are described in the separate Baltic MANURE report "Examples of existing good practices in manure energy use" (available at http://www.balticmanure.eu).
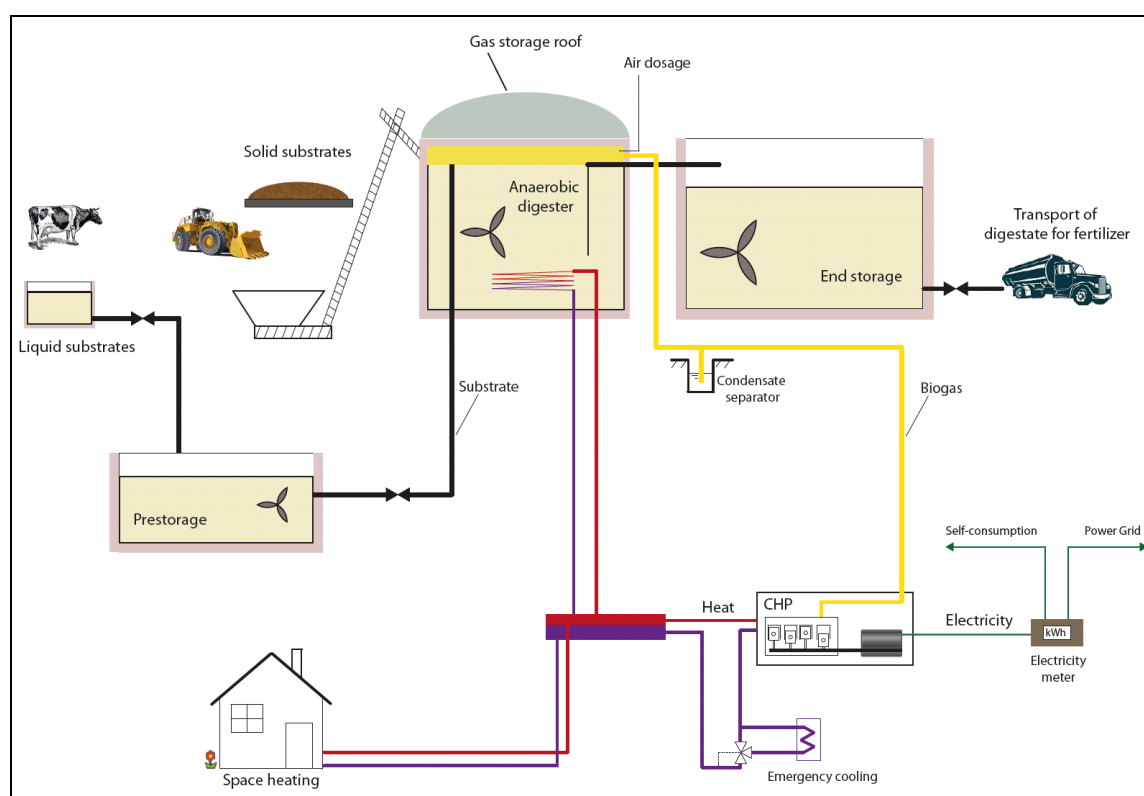

Figure 4. A centralised biogas plant in Güstrow, Mecklenburg-Western Pomerania in Germany. Photo: EnviTec Biogas AG (reprinted with permission).

Centralised biogas plants may also aim at producing targeted fertiliser products instead of plain digestate. In many cases, transportation of the large amounts of digestate to the fields would be

too costly as the amount of nutrients requires a large field area for spreading. Thus, post-processing of the digestate may offer the solution for efficient reuse of the nutrients. Usually the digestate is firstly mechanically separated into solid and liquid fractions. The solid fraction may be further dried and pressed into pellets to provide a phosphorus-rich fertiliser or material for incineration or thermal gasification (see: Baltic MANURE reports on manure use for incineration and thermal gasification). For the liquid fraction, there are many process technologies available and/or under development. For example in Finnish centralised biogas plants, technologies, such as ammonia stripping, evaporation,

4.2   Digester technologies

There are several different digester technologies used for anaerobic digestion. Olsson et al. (2005) have divided biogas technology into three generations by level of technological approach and increase of bioconversion capacity (Figure 5), though not all of the technologies described are suitable for all types of raw materials. While CSTR is still the most common and widely-used process for digestion of manure, energy crops and diverse municipal and industrial raw materials, upflow anaerobic sludge blanket (UASB), expanded bed (such as internal circulation reactor IC) and fluidised bed are only suitable for more dilute materials, i.e. mostly wastewaters.
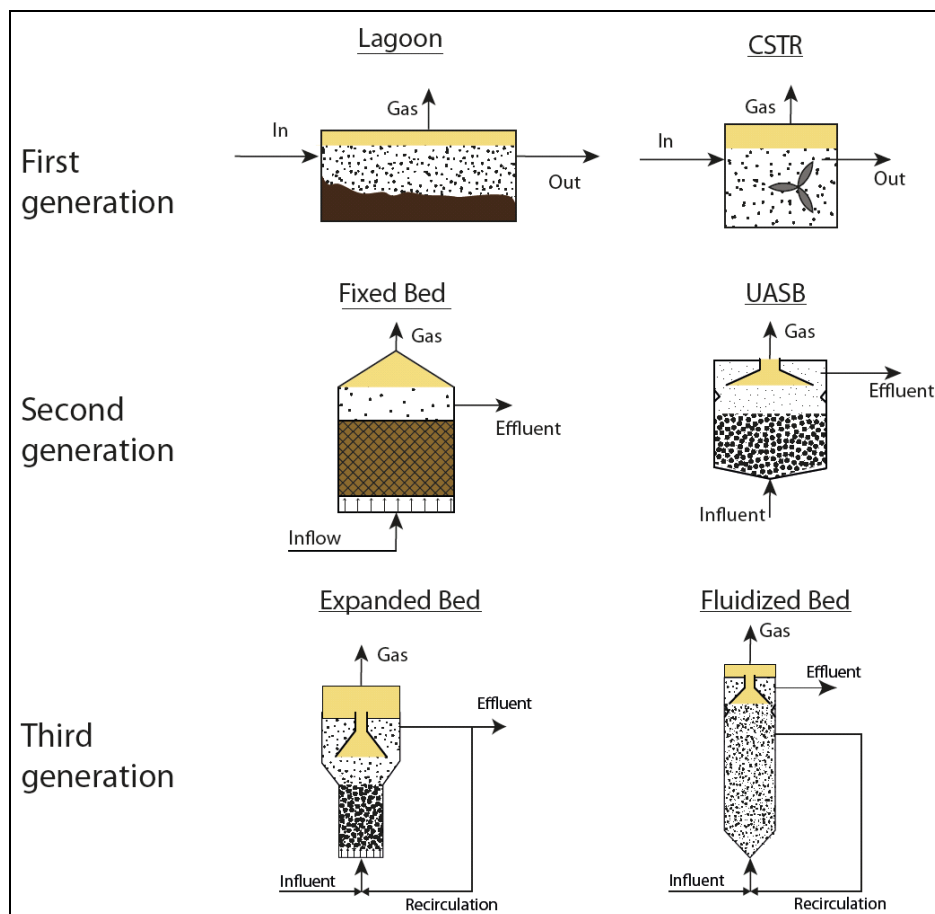

Figure 5. Some examples of anaerobic digestion technologies: CSTR – Completely Stirred Tank Reactor; UASB – Upflow Anaerobic Sludge Blanket Reactor (Olsson et al., 2005; Chynoweth, 1987).

Agricultural digesters are usually described by construction of digester and process technology (a rough overview of digester characteristics, Table 5). A single (one-stage) CSTR is a common digester in agriculture with continuous feeding of manure and/or energy crops (e.g. maize and/or grass silage), with the process temperature in mesophilic range from 35 to 40 ºC (see: chapter 2.2). The plant may also be two- or multi-staged. In agricultural biogas plants this usually refers to the main reactor with temperature control and a separate post-digestion tank with biogas collection (see more details in chapter 4.4). Also a pre-reactor may be used for separating hydrolysis and acidification into one tank and the methane producing phase into another, the ultimate being optimisation of the conditions for the degradation phases.

Table 5. Main characteristics of anaerobic digester technology in agricultural biogas plants (Institut für Energetik und Umwelt et al., 2006; Chynoweth, 1987).

Characteristic	Technology
Construction of digester	completely stirred tank, plug-flow, lagoon, etc.
Temperature in digester	psychrophilic, mesophilic, thermophilic
Process stages	one-stage, two-stage, multiple stages
Loading strategy	batch, continuous, semi-batch
Environment in digester	dry, wet

4.2.1 Continuous wet and dry processes

Continuously fed biogas plants are filled and then emptied by different strategies. Wet processes (TS <14%, raw materials which are readily solubilised or already suitable for pumping) are often CSTRs fed in certain intervals (a few times per day or per hour) with simultaneous withdrawal (often by gravity) of digestate (Fig. 6). The biogas production is thus rather constant, but as the new feed is mixed into the reactor contents, some by-pass occurs (i.e. not all raw material stays the whole HRT in the reactor). On the other hand, mixing efficiently provides good contact between the raw materials and the microbes, no re-inoculation is required, the reactor content is homogeneous, and the reactor temperature stays stable.

Continuous feeding may also be performed for raw materials with high TS content, such as food waste. A common reactor type is plug-flow (Fig. 6), meaning a vertical cylinder being fed from one end and emptied from the other and using e.g. belts for transporting the materials. The raw material is firstly mixed with already digested material to provide the necessary microbial inoculum, which needs to be taken into account when designing the process. The process may also contain collection and recirculation of leachate from the digested material, further facilitating contact between the digested material and the microbes. The greatest challenge of these dry processes is mixing: the digestate is often still unstabilised and requires post-treatment, such as composting. The mixing may also be inadequate for ensuring efficient biogas release and collection as well as stable temperature in the reactor content.

Figure 6. Different digester configurations. Two CSTRs digesting energy crops and a hooded post-digestion tank (top left), A plug-flow digester treating food waste (top right). A farm-scale CSTR treating pig manure and energy crops (bottom left). Garage-type batch digester treating manure from a zoo (bottom right). Photos: Sari Luostarinen & Teija Paavola, MTT.

4.2.2 Batch dry processes

Batch operation is usually used for raw materials with high TS content, such as solid manure. A garage type is probably the most common batch reactor (Fig. 6). It is filled with a mixture of new raw material and digestate (to provide inoculum) using e.g. a front loader, then closed for biogas producing period of at least 20-30 days, and finally opened and emptied just to start the cycle again with new filling. As the biogas production thus varies depending on the stage of the operational cycle, it is usual to have at least three parallel batches in different stages of operation: one being filled, one in biogas producing phase and one being emptied. Also the batch digester may

4.3 Pre-treatments

Different pre-treatments may be used prior to the actual biogas reactor in order to i) improve the degradation of the raw materials (higher VS removal), ii) increase biogas production, iii) ensure the hygienic quality of the digestate, iv) facilitate technical functions (e.g. prevent blockages), v) ensure homogenous feed and reactor biomass (e.g. large particles of plant biomass float more easily than smaller ones), vi) remove potentially inhibitive compounds, and/or viii) enable process

intensification (higher OLR, shorter HRT, smaller reactor size). Many of the pre-treatments used facilitate more than one of the benefits mentioned simultaneously.

4.3.1 *Size reduction*

Many raw materials for biogas processes are macerated (food waste, industrial by-products) or chopped (plant biomass) before feeding into the digester in order to decrease the particle size. Of the different manure types, usually only solid manures with larger particles from bedding material may require maceration/chopping, while liquid manure is usually just pre-mixed to ensure homogeneousness prior to feeding. However, for example energy crops and crop residues are chopped into smaller pieces in order to increase the surface area for hydrolytic enzymes to attack and thus to release more soluble components (Palmowski & Müller 1999). This aims at facilitating improved degradation and higher biogas yield. The smaller particles are also easier to convey into the digester via e.g. feed screws as they do not entangle themselves into the feeding device nor into the mixers inside the reactor. They also stay more efficiently within the digester biomass and are less prone to floating. Legislation may also require pre-maceration. E.g. the European Union regulation for using animal by-products (ABP) in biogas plants requires <12 mm particle size for materials also to be pre-hygienised (see below) or <50 mm for materials also to be pre-sterilised (see below; 1774/2002/EC).

4.3.2 *Thermal treatment*

Hygienisation (70 $^{\circ}$, 1 h; 1774/2002/EC) or sterilisation (133 $^{\circ}$C, 3 bar 20 min; 1774/2002/EC) may be used as a pre-treatments to biogas processes, especially in plants treating ABPs or other raw materials with potential hygienic risks. Also, thermal hydrolysis (e.g. CAMBI-process: 165-170 $^{\circ}$C, 6 bar, 30 min; Sargalski et al., 2007) is used. These thermal pre-treatments not only ensure the elimination of pathogens, but also loosen the solid structures via pressure changes (Bougrier et al., 2005) and result in more degradation (higher VS removal) and higher biogas production (Sargalski et al., 2007). For example Mladenovska et al. (2006) reported the BMP of cattle manure to increase by 10-24% after thermal pre-treatment (100, 120 or 140 $^{\circ}$C, 20 or 40 min), while during continuous experiments (HRT 18 d, 55 $^{\circ}$C), the increase due to thermal pre-treatment (140 $^{\circ}$C , 40 min) was 7%. Moreover, Paavola et al. (2006) noticed an increase in methane yield of 14-30% due to hygienisation, while co-digesting manure and food waste (feed 5 d/week).

4.3.3 *Pre-separation*

Some sludge-like materials may also be mechanically pre-separated (see chapter 4.4.2) with only the solid fraction intended for the biogas process in order to e.g. minimise transportation needs. On farms, mechanical pre-separation of liquid manure may also resolve problems with regard to excess phosphorous. Most of the manure phosphorous is contained in the solid fraction and could be thus exported out of the farm into e.g. a joint biogas plant for several farms. The farm may then utilise the more nitrogen-rich liquid fraction as organic fertiliser and possibly receive only the amount of digestate they need for phosphorous fertilising. The biogas plant may thus redistribute the nutrients within the cooperating farms, with some farms receiving more nutrients than their raw material input into the plant, and some farms receiving fewer nutrients than their nutrient input. The plant may also sell or hand out some of the digestate to third parties, thus relieving the nutrient surplus in the cooperative farms.

4.3.4 Sonication, enzyme addition and other

Other pre-treatments applied in full scale or under development are e.g. sonication, enzymatic hydrolysis, addition of acids and bases, chemical oxidation and radiation. Sonication is mainly applied as a pre-treatment for sewage sludge and waste activated sludge (e.g. Nickel & Neis, 2007), while as manure pre-treatment it has not been applied (Luste & Luostarinen, in Press). The ultrasound waves evoke cavitation by bubble formation in the liquid phase. The collapse of the bubbles then produces local heating and pressure at the gas/liquid interface, turbulence, formation of radicals and shearing, resulting in solubilisation of the treated raw materials (Thiem et al., 1997; Gonze et al., 1999). Low ultrasound frequencies of 20-40 kHz are reported the most efficient in disintegrating cellular structures (Thiem et al., 1997; Laurent et al., 2009) and resulting in increased VS removal and biogas production. Enzymatic hydrolysis, in turn, aims at enhancing the natural degradation via hydrolytic enzymes in the biogas process with addition of either pure enzymes (e.g. amylases) or of hydrolytic bacteria. Enzymatic hydrolysis has been studied for years with different raw materials and the results obtained are rather controversial: some report increased degradation and biogas production, some no effect. The situation is rather similar also for chemical hydrolysis and radiation.

4.4 Post-treatments

4.4.1 Post-digestion tank

A post-digestion tank is an integral part of all biogas plants as it allows the feed to continue degradation and collects the remaining biogas potential in a controlled manner, This is not only important for minimising methane emissions of biogas plants, but also offers a significant increase in the overall biogas production of the plant. The remaining biogas potential of any digester residue is significant and may provide 10-30% of the overall biogas production in a biogas plant.

Post-digestion tank is thus situated after the actual digester. The bigger the biogas plant, the shorter the HRT in the post-digestion tank is, due to the large quantities of raw materials digested and the subsequent need for high post-digestion volume. However, in smaller (farm-scale) plants the post-digestion tank may be as big as or larger than the actual digester thus providing at least another HRT period of controlled degradation and collection of the remaining biogas potential. Post-digestion tank may also serve as the sole digestate storage on farms prior to field application. In this case its volume equals the manure volume to be stored (e.g. 12 month storage capacity in Finland). The post-digestion tank is not heated as the digester, but the temperature may change depending on the tank design and weather conditions. When situated mostly underground and insulated, the digester temperature can almost be maintained (digester 37 °C, post-digestion tank 29-35 °C) despite no heating and very cold winters (-20…-30 °C for several weeks; Luostarinen, 2011).

4.4.2 Mechanical separation of digestate

The digestate can be mechanically separated into liquid and solid fractions which can then be utilised as fertilising and/or soil improving products as such or post-processed further (see below). Mechanical separation can be performed with different technologies, and the technology choice

affects the separation efficiency. Also, the characteristics of the digestate influence the end result. For example settling (or sedimentation) of materials with high water content are based on differences in the mass and density of the components to be separated. Most of organic nitrogen and phosphorus are retained in the solid fraction, but soluble nutrients are left in the liquid fraction. Very fine materials pose a problem as their separation is difficult with mere settling (Vanotti & Hunt, 1999).

Centrifuging is also based on the differences in mass and density of the components to be separated, but the efficiency is significantly higher than with settling. By increasing the spinning velocity, 1000-4000 times higher acceleration than that of the globe can be achieved. Thus, centrifuging is reportedly the most efficient way to separate both phosphorus and solids. The efficiency can in some cases be further increased by addition of polymers (Hjorth, 2009). There are different centrifuges available, a decanter centrifuge being the most common and efficient. When separating liquid manures, decanter centrifuge is estimated to be able to separate particles as small as 20-25 μm (Hjorth, 2009) and even part of the particles of <4 μm (Sneath, 1988).

Separation based on sieving can be implemented with different processes, such as screw dryers and press belts. The liquid is pressed through sieves or canvasses with the solid fraction being retained behind it. Sieving processes cannot separate particles smaller than the sieve size, usually 0.5-1 mm, which is larger than most particles in raw manure (Møller et al., 2002) and most likely even more so, when separating digestate.

4.4.3 *Post-processing of digestate solid fraction*

The liquid and solid fractions from mechanical separation may be processed further in order to produce more targeted fertiliser products. The solid fraction may be post-composted into e.g. culture medium. It can also be dried further (using the waste heat form the biogas plant) and pressed into pellets, while the liquid fraction may be subjected to e.g. ammonia stripping or membrane separation. The pellets can be used as ready-made, phosphorus-rich fertiliser products or they can be directed to combustion. Thermal gasification of manure (raw or digested) pellets is also under demonstration phase in Denmark (see: a separate Baltic MANURE report on thermal gasification available at http://www.balticmanure.eu).

4.4.4 *Post-processing of digestate liquid fraction*

In ammonia stripping (Figure 7), ammonia is stripped from the liquid fraction of the digestate into gaseous phase by increasing the pH (usually 11) and/or temperature (usually 70 °C) to facilitate conversion of ammonium nitrogen to ammonia and then blowing the liquid with e.g. air in order to make the easily evaporative ammonia shift into the gaseous phase. The process is performed in a vertical column with liquid feed from the top and removal from the bottom, while the air is blown from the bottom. The ammonia-rich gas is then directed to a recovery zone in which ammonia is recovered into scrubbing liquid, e.g. water, sulphuric acid or nitric acid (Metcalf & Eddy, 2003). The resulting ammonium water, ammonium sulphate or ammonium nitrite can be used as fertilisers or e.g. in scrubbing of combustion gases (Rulkens et al., 1998). Reportedly, recovery efficiency of over 90% may be possible for stripping raw and digested pig manure, though

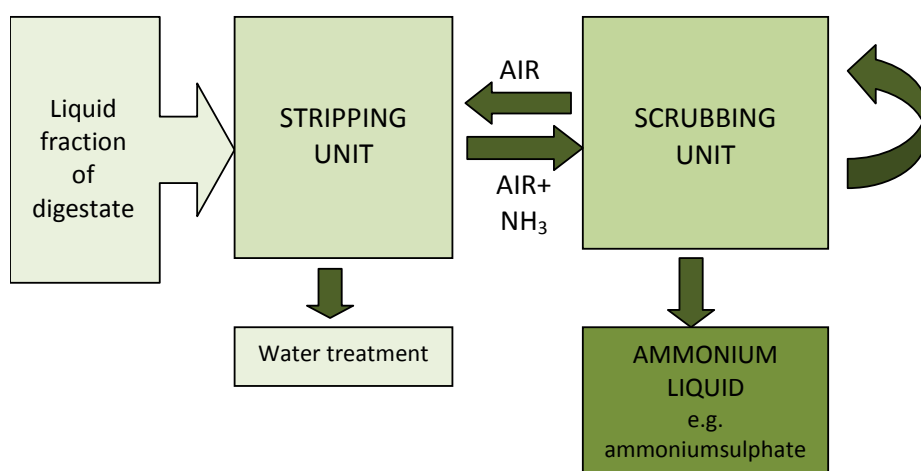with digested pig manure the requirement for pH elevation was significantly lower (Bonmati & Flotats, 2003).

FIGURE 7. The principle of ammonia stripping.

Membrane technologies are based on semipermeable membranes which retain particles and compounds larger than their pores (retentant or concentrate) and let only the smaller ones through (permeate). Membranes may separate as small particles as bacteria, viruses and chemical compounds (Burton, 2007). Usually the separation is facilitated by pressure difference over the membrane (movement from concentrated to dilute as in diffusion). Reverse osmosis is also possible and is based on such high pressure difference over the feed and permeate interface that the osmotic pressure is overcome and salts can be separated.

Membrane technologies are classified after the pore size of the membrane (Table 6) and the membranes are required to be selective, permeable, mechanically durable, temperature tolerant and chemically resistant. The most challenging part of membrane technologies is the membrane fouling, i.e. becoming dirty and blocked, with resulting requirements for counter current or chemical washing. Usually materials with high organic matter content require pre-treatment with settling, coarse filtration or biological treatment (Fugere et al., 2005; Masse et al., 2007). Still, membrane technologies may provide efficient concentration of nutrients from the liquid fraction of digestate and are in full-scale use, e.g. in Germany. A benefit is also that the process water to be treated further may be pure enough for direct discharge into the environment or at least sufficiently dilute to be successfully treated at the local wastewater treatment plant.

TABLE 6. Classification of membrane technologies.

Technology	Pore size (µm)	Pressure difference	Retains
Microfiltration	0.1-5	100-500 kPa	solids, bacteria, grease
Ultrafiltration	0.005-0.1	100-800 kPa	viruses, some proteins
Nanofiltration	0.001-0.01	0.3-3 MPa	pesticides, viruses, proteins
Reverse osmosis	0.0001-0.005	1-10 MPa	salts, odour, taste, colour

The liquid fraction may also be placed in vacuum evaporator with the intention of evaporating water and volatile compounds, such as VFA. Acid is usually added in to liquid to be evaporated in order to remove dissolved carbon dioxide and prevent salt precipitation. The remaining concentrate can be used as fertiliser, while the evaporated compounds are condensed separately. The condensate may contain sufficiently high concentration of organic matter to require treatment prior to discharge.

5 Energy use of biogas

Biogas is a versatile, renewable fuel that can be used for production of heat, electricity and/or vehicle fuel. Biogas can be combusted in gas boilers to produce heat or in gas engines or turbines to produce both electricity and heat. It can also be upgraded to vehicle fuel quality by increasing the methane content through removal of most of the other compounds present.

5.1 Biogas composition

Biogas contains mainly methane (55-70%), while the rest is mostly carbon dioxide. One cubic meter of biogas (at 60% methane) contains approximately 22 MJ of energy (lower heating value), while the methane content alone contains roughly 36 MJ (10 kWh). Small quantities of other gaseous compounds such as hydrogen, hydrogen sulphide, ammonia, oxygen, nitrogen, silicon dioxide and particulates are also present depending on process technology and the raw materials digested (Jönsson et al., 2003). In addition, biogas is generally saturated with water when it leaves the digester. The saturation level is strongly dependent on the gas temperature. For example, saturated biogas at 30 °C has a water content of 30 g/m^3 biogas, while at 40 °C, the same gas has a water content of 52 g/m^3 biogas. This means that the water content in the biogas leaving the digester is higher at thermophilic digestion compare to mesophilic (Hillen et al., 2010a). The demand for water reducing pre-treatment (drying) before biogas utilisation depends on the energy use.

5.2 Compounds in biogas that are disruptive to energy utilisation

In gas pipes and gas storage, the biogas temperature generally drops below the dew point, causing water to condense. The condensate must be drained off from the gas system through gas-tight piping and disposed off. Condensing can also be used as the drying method; i.e. the biogas is by design directed through a well/section in the pipeline in which the temperature is below the dew point and the condensed water is removed from the gas.

Sulphuric compounds, such as hydrogen sulphide (H_2S), may cause corrosion in the presence of water (Persson et al., 2006) and depending on their concentration, may also be required to be removed from the biogas before energy use. Additionally, hydrogen sulphide is a toxic gas and can have negative health effects in high concentrations and measures should be taken to protect the operational staff. Also, organic silicon compounds oxidise to microcrystalline silicon dioxide during biogas combustion and are deposited on valves, cylinder walls and liners, causing abrasion and blockages (Tower, 2003). They may also end up in engine oil, resulting in more frequent oil

changes, and some manufacturers have set a limit of 1 mg silicon / litre of oil in gas engines for warranties to be valid (Accettola & Haberbauer, 2005).

Also ammonia (NH_3), in conjunction with condensation, can cause corrosion and under certain conditions also result in the formation of deposits in the fuel gas system. This deposition can further on result in component wear and reduced filter service life. Particulate matter and droplets can also cause formation of deposits, reduced filter service life and dirt contamination (Hillen et al., 2010a).

Impurities in the biogas brought into the engine affect the exhaust gas treatment systems and the exhaust gas emissions. For example, hydrogen sulphide in the biogas results in an increased value of sulphuric acid, while ammonia increases the nitrogen oxide emissions. Moreover, oxidation catalysts are sensitive to impurities, such as silicon or sulphur (Hillen et al., 2010a).

The requirements with regards to the purity of the biogas increase the more specialized the energy use becomes. Heat boilers are usually robust and require only water removal, while gas engines and turbines for heat and power production (CHP) and especially use as vehicle fuel require more biogas pre-processing before utilisation. Examples on biogas pre-processing steps are drying, desulphurisation and removal of carbon dioxide.

5.3 Biogas in heat production

The easiest way of utilising biogas is to produce heat in a boiler. The technology has low investment and maintenance costs and is well-known and reliable. For small scale biogas plants located at a site with a high heat demand, it is probably the best alternative, at least in countries with rather low price for electricity produced with biogas. The heat demand at a farm during summer can, as a monthly average, be about 20% compared with a winter month (Edström et al., 2008). Therefore, localization close to a site with a high demand for heat the whole year around can be favourable. One option can also be to invest in an enterprise needing a lot of heat during summer time. Drying of wood chips is an example of such an enterprise. Biogas can also be used for steam production in industrial applications, where the seasonal variation in heat demand is low. Application for heating greenhouses can bring extra value since the carbon dioxide content of the exhaust gases can be used to promote growth in the greenhouse (Christensson et al., 2009). Refrigeration plants can also use heat from biogas for sorption cooling although this use is not currently wide spread.

In boilers, the requirements for biogas quality are low but it is recommended to reduce the level of hydrogen sulphide content below 1.000 ppm, which allows the exhaust gases to maintain a dew point around 150 °C (Persson et al., 2006). It is also rather important to maintain an even concentration of methane in the biogas over time. The composition of the biogas, especially the methane content, affect the Wobbe index (defined by the calorific value divided by the square root of the relative density) and is important when designing biogas utilization components, for example a nozzle for a burner.

5.4   Biogas in combined heat and power production (CHP)

CHP generation is the standard utilisation of biogas and considered very efficient for energy production. The technologies to convert biogas into electricity and heat are numerous and in general it is not complicated to connect to the electricity grid, although it is important to have a legislation promoting the connection to the electrical grid for small scale power plants. Most common CHPs are ordinary diesel or otto engines using biogas as fuel. Other methods are gas turbines, Stirling motors, Rankine cycles and fuel cells.

Before the CHP, biogas is drained and dried. In most technologies there is also a maximum limit for the content of hydrogen sulphide, halogenated hydrocarbons and siloxanes in biogas.

In the CHP application, the production of heat is larger than the production of electricity, usually in the ratio of 30-40% electricity and 60-70% heat (Fig. 8). Therefore, it is crucial to have a high utilisation of the heat produced for overall energy efficiency and for the biogas plant economy. Part of the electricity and heat produced is also utilized by the plant itself for maintaining the reactor temperature, mixing, pumping etc. and the less this consumption is, the more profits can be made from selling the energy produced outside or from utilizing it to replace energy purchased from the grid.

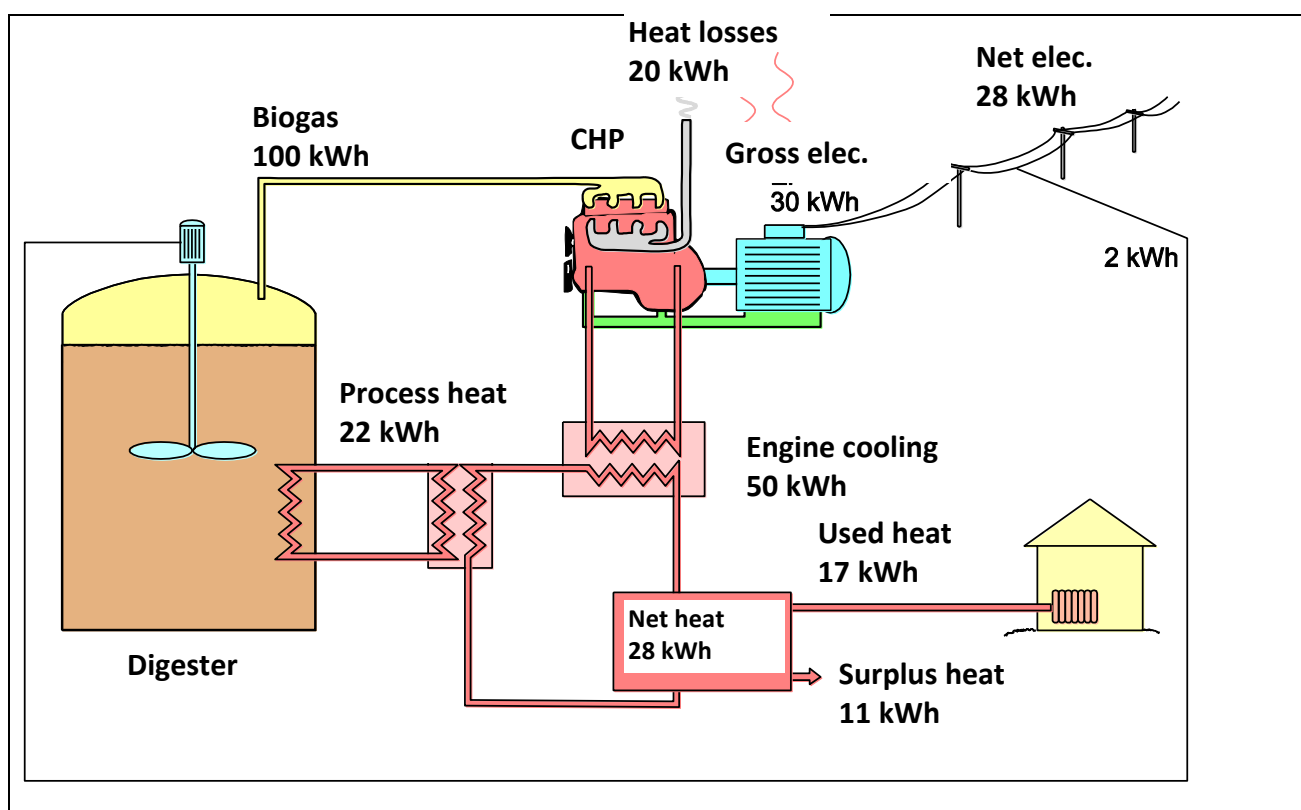*Figure 8. An example on energy flow for a small farm-scale biogas plant digesting liquid manure and using the biogas produced for CHP. 100 kWh biogas is fed to the CHP. The process energy demand for running the digestion process is 2 kWh electricity and 22 kWh heat. The net production of both electricity and heat is 28 kWh, respectively, and as an annual average 17 kWh heat is used for buildings (Edström et al., 2008).*

5.4.1   Otto and diesel engines

In traditional CHP applications, ordinary otto or diesel engines (both are internal combustion engines), adapted to biogas as fuel, are well-known technologies.

Using biogas as fuel in a diesel engine (Fig. 9), the heat of compression is not enough for self-ignition. Therefore, diesel engine uses a second oil-based fuel, together with biogas, for ignition. The biogas is mixed with the combustion air. The oil-based fuel is injected near the top of the compression stroke where it immediately ignites by the compression heat together with the biogas. A common name for these diesel engines is dual-fuel engines or pilot injection engines. The ignition oil can be fossil diesel or heating oil, but renewable rapeseed-methyl-ester (biodiesel) can also be used. Usually the oil injection is 2 - 5% during normal conditions (FNR, 2010). This can be compared with the German evaluation program "Biogas Messprogram II" (2009) which reports a 3.8-18 % oil injection for 43 diesel engines with 9.2% as an average. In case of disrupted biogas supply, dual fuel engines can also operate with diesel, without any problem. During a start-up phase, this is an advantage due to the high demand for process heat and low production of biogas.

Figure 9. Dual-fuel engine for CHP with biogas. Photo:Mats Edström, JTI.

Otto engines only use biogas as fuel. They have spark plugs for ignition and a gas/air mixing system for providing a combustible mixture to the engine. Otto engines are constructed for power generation using a lean burn technology, including turbocharger, with a surplus of air for improving efficiency and reducing emissions (FNR, 2010). Diesel engines can also be re-built to otto engines, when using only biogas as fuel, by adding an ignition system. Gas-otto motors require biogas with a minimum of 45% methane content.

The German evaluation program "Biogas Messprogram II" (2009) reports that electrical efficiencies were 30.5-42.4% and 36.5% as an average for the internal combustion engines. The otto engines reviewed in the study had a name plate electrical power between 46 to 1064 kW and the diesel engines between 48 to 300 kW. For otto engines the average electrical efficiency was approx. 35% and for diesel engines approx. 38%. Lantz (2010) also report differences in electrical efficiency between otto and diesel engines and at similar size, the difference is in general approx. 5% to the benefit of diesel engines (Fig. 10a). It is, however, important to notice that a good otto engine can have higher electrical efficiency than a poor diesel engine. Furthermore, the electrical efficiency generally increases with engine size.

Contradictory, the thermal efficiency decreases with engine size (Fig. 10 b). In general the thermal efficiency is 5-10% higher for an otto engine compared with a diesel (Eder & Schulz, 2006) and the difference is larger between engines of low electrical power.
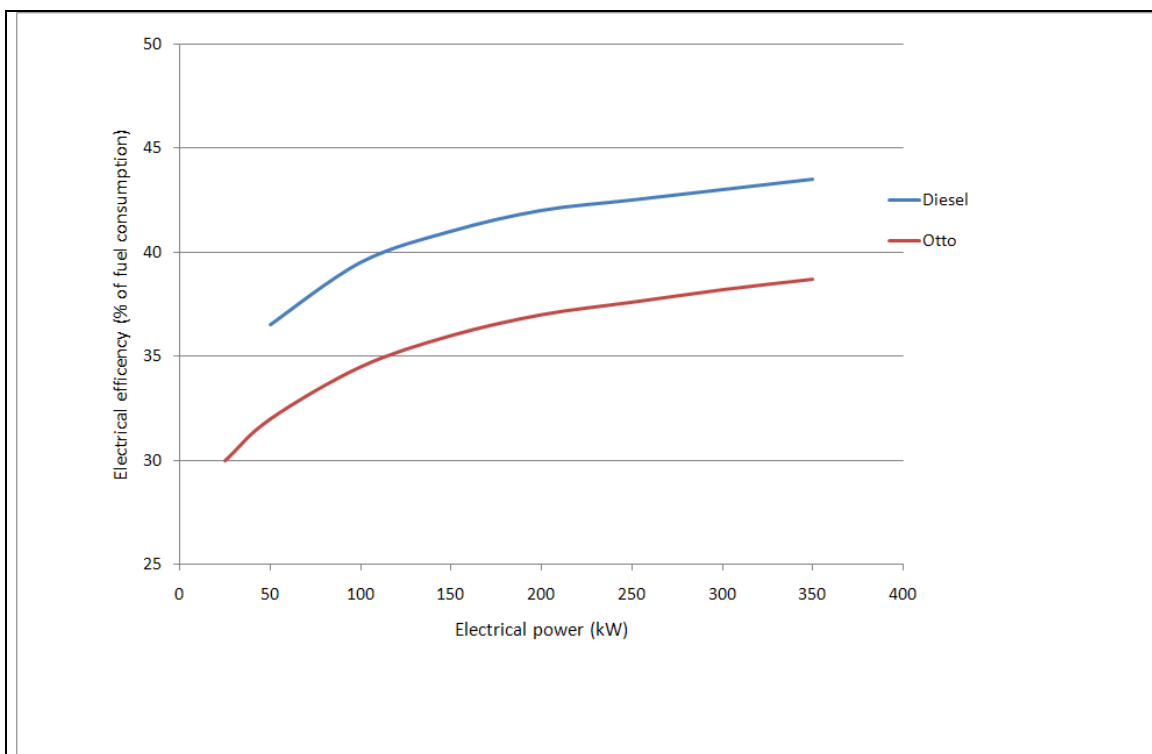

Figure 10a. General relations of electrical efficiency between otto and diesel engines versus installed electrical power (based on Lantz, 2010).
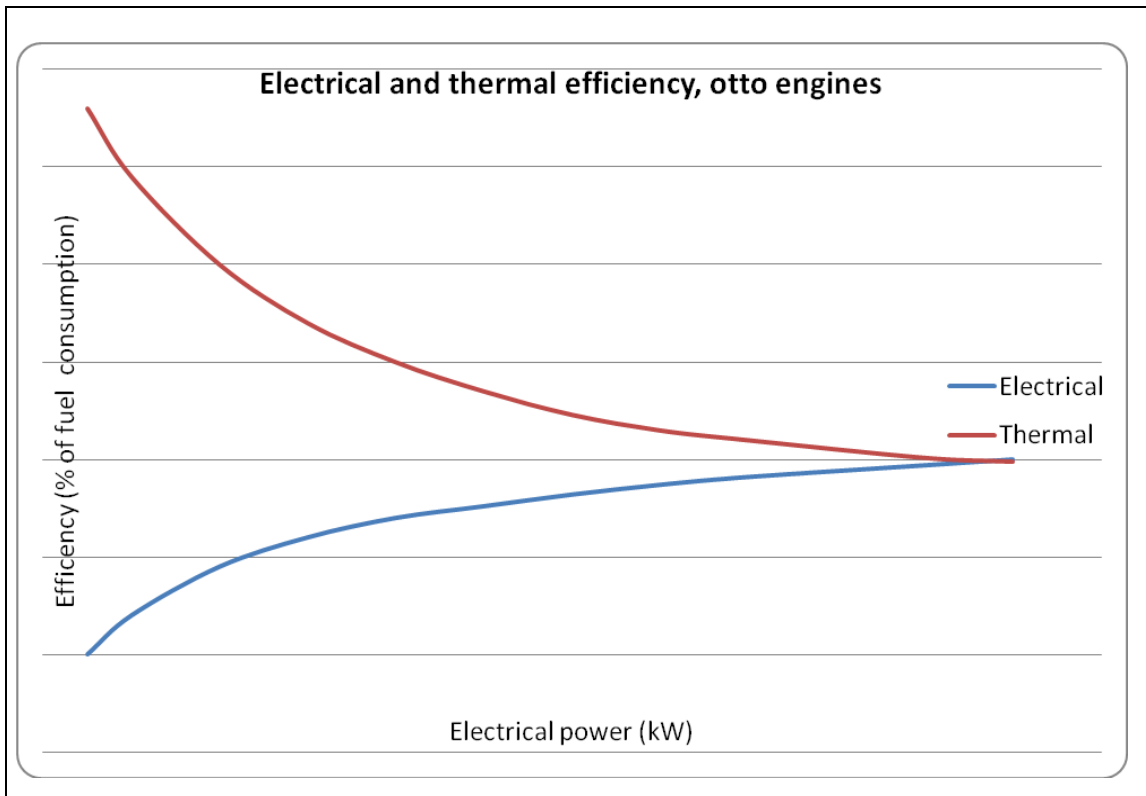
Figure 10b. General relation between electrical and thermal efficiency versus installed electrical power for otto engines using biogas as fuel (based on Lantz, 2010).

According to FNR (2010), the life expectancy of a diesel engine is 35 000 hours and of an otto engine constructed for power generation with biogas as fuel 60 000 h.

5.4.2   *Gas turbine*

Modern gas turbines are derivatives from aviation gas turbine in which exhaust gases are directly expanded through the turbine and the plant size is often 40 - 50 MW$_{el}$. The fact that the exhaust gases expand directly in the turbine wheel, poses strict fuel purity requirements (Nymberopoulos, 2004). Today, there is a well-established market for smaller gas turbines for CHP-production at sizes above 800 kW, but also smaller turbines, called microturbines (Fig. 11), have been successfully introduced for biogas applications (Persson et al., 2006).

Microturbines are gas turbines with a power ranging approximately from 10 to 200 kW. Microturbines are very simple systems having only one moving component: the high speed shaft (over 60,000 rpm and up to 105,000 rpm) supporting the compressor, turbine wheel and generator (Vasen et al., 2004). A microturbine operates on the same general principle as a conventional gas turbine that consists of (Nymberopoulos, 2004):

- Incoming combustion air being compressed to 3 - 5 bar by a single stage centrifugal compressor (Fig. 11)
- Compressed combustion air passing through a recuperator, recovering some of the energy of the exhaust gases; fuel and combustion air being injected into the combustor with the temperatures reaching 900 to 1000 ^{o}C

- Hot exhaust gases expanding through the usually single-staged, radial turbine, dropping their temperature to approx. 650 ^oC; turbine being the device for production of mechanical work being fed into the single microturbine shaft
- Exhaust gases then passing through the recuperator with a temperature drop to 250-350 ^oC
- The exhaust gases finally passing another heat exchanger to recover heat for hot water or air for heating purposes (or chilling through an absorption chiller) or steam production
- Mechanical work being fed into the compressor and the high speed generator producing a high frequency power that is converted to the desired voltage and frequency through a power conditioning system

1. Generator	7. Recuperator
2. Air inlet	8. Exhaust gases
3. Compressor	9. Heat exchanger
4. Air to recuperator	10. Exhaust gas outlet
5. Combustion chamber	11. Hot water outlet
6. Turbine	12. Water inlet
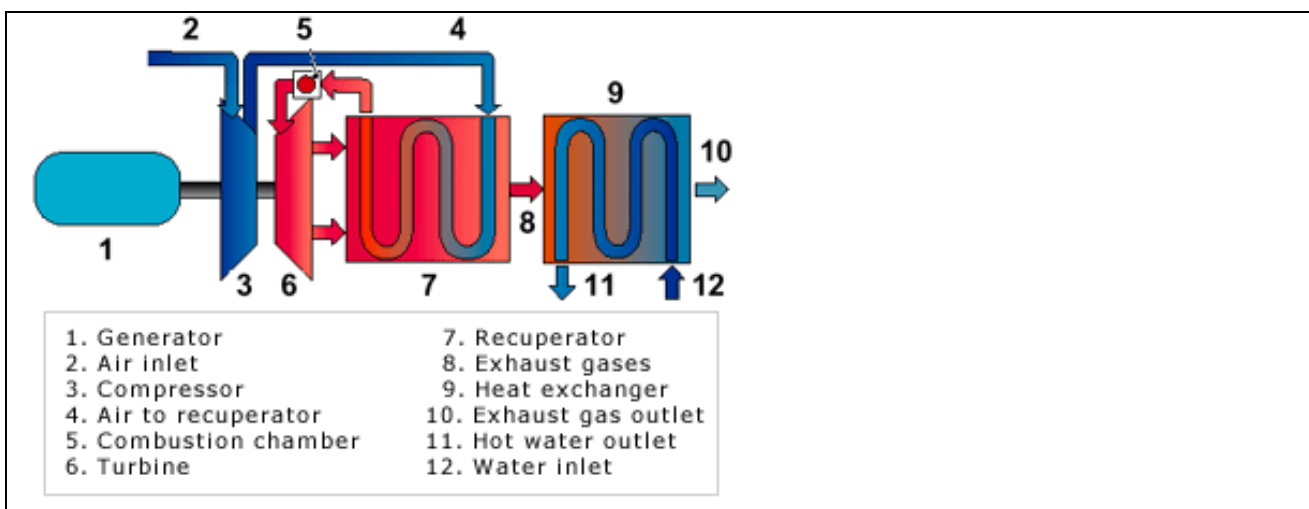
Figure 11. Principal function for a microturbine with recuperator (from http://www.turbec.com).

Advantages of microturbines are (Vasen et al., 2004):
- Low maintenance
- Very compact
- High reliability
- Low emissions
- Flexible to use different fuels
- Heat production at high temperature is possible
- Silent compared with internal combustion engines
- Long life expectancy, 60 000 – 80 000 hours (Lantz, 2010)
- Use low energy biogas with methane content down to 35 % (Nymberopoulos, 2004).

Disadvantages of microturbines are:
- High investment
- Rather low electrical efficiency
- Sensitive to impurities in biogas

In Table 7 some examples on emission levels are shown for two different microturbines from tests with natural gas and biogas. Fig. 12 shows one farm-scale example of microturbine.

Table mtx. Measured emissions at tests with microturbines.

	Turbec T100 Laboratory test	Turbec T100 Field test	Capstone, C30 [2) Laboratory test	Unit
Fuel	Natural gas	Biogas, 58 % CH_4	Natural gas	
Electrical power at test	100	100	27.4	kW
In operation before test	-	19 000	-	Hours
Electrical efficiency	31,5	27.4± 1.2	22.6 [3)	% of added fuel
Thermal efficiency	44-50 [1)	Ca 40	-	% of added fuel
NO_x emissions	3.3 – 3.5	7,.6-7.8	4	ppm
SO_2 emissions	1-4	-		ppm
CO emissions	0-4	0	16	ppm
Source	Colombo et al., 2007	Brown et al., 2010	Pierce, 2007	

1) Outlet water temperature from exhaust gas exchanger from $80 – 60\ ^oC$
2) Emissions at 18,5 % O_2
3) Based on HHV

Figure 12. Microturbine installation at Hagavik farm-scale biogas plant, Sweden. Photo:Mats Edström, JTI.

5.4.3 *Stirling*

The principle of the Stirling engine has been known for close to 200 years. The working principle of all types of piston engines is to compress a cold gas in a cylinder, apply heat to increase the gas temperature and thereby the pressure, and finally expand the hot gas in the cylinder. The main difference between the Stirling engine and the otto/diesel engines is the combustion cycle. The otto and diesel engines are internal combustion engines, in which a mixture of combustion air and fuel are ignited and combusted inside the cylinder. In the Stirling engine, the fuel is combusted in

an external combustion system and the generated heat from the combustion is transferred to the working gas in the cylinder.

In principal a Stirling engine includes two cylinders connected with each other with a pipe for transporting the working gas between the cylinders. One cylinder is heated by the external heat source and the other is kept cool. The Stirling cycle can in general terms be described in the following four parts:

1. Cool gas is compressed (by a piston) inside the cool cylinder
2. The cool working gas with high pressure leaves the cool cylinder and is transported through a pipe into the warm cylinder
3. The working gas is heated by the hot cylinder and expands making the piston move and generating mechanical work
4. The warm working gas with low pressure leaves the hot cylinder and is transported back into the cold cylinder through a pipe.

To improve the efficiency, the pipe also includes a heat exchanger to cool or to heat the working gas depending whether the Stirling cycle is in stage 2 or 4.

The heat input from the combustion of fuel is transferred from the outside to the working gas at a high temperature (typically 700 – 750 °C). The heat, which is not converted into work on the shaft, is rejected into the cooling water at 40 - 85°C (www.stirling.dk).

Since the combustion takes place outside the cylinder and the combustion products do not come into contact with the internal parts of the engine, almost any kind of fuel can be used as the heat source.

A Stirling engine has two power pulses per revolution and the combustion is continuous. These qualities make Stirling engines operate smoothly, resulting in lower vibration, noise level and emissions than for internal combustion engines (Öberg et al., 2004).

In theory, the Stirling cycle has the highest efficiency attainable by any heat engine process (equal to a Carnot cycle). In practice, the heat exchanger (attached to the pipe for transporting working gas between the cylinders) in the Stirling engine is not efficient enough, for reaching the theoretical efficiency of the Stirling cycle. Also, the unit for transferring heat from the combustion chamber to the working gas is one of the key components in the Stirling engine, being technically advanced due to the requirements of good heat transfer properties, high operating temperature (600 - 700 ^{o}C) and high operating pressure (10 - 15 MPa), all of which makes it necessary to use high-tech materials and manufacturing methods (Öberg et al., 2004). In Table 8 some characteristic performance parameters for a Stirling engine are shown.

Table 8. Efficiency and emissions for some Stirling engines.

	SOLO 161	V.161	SD4-E	Unit
Test conditions	Field test	Manufacture	Manufacture	
Fuel	Natural gas	Biogas/Natural gas	Gasification gas	
Electrical power at test	7.3	9	35	kW
Electrical efficiency	25.4	25	28	% of added fuel
Thermal efficiency	52.4	67-71	Ca 70	% of added fuel
NO$_x$ emissions	14 [1]	80 [3]	-	ppm
CO emissions	112 [1]	50 [3]	-	ppm
HC emissions	< 1 [1]	-	-	ppm
Life expectancy	-	-	100 000	h
Ref.	Öberg et al., 2007	Cleanergy AB	Stirling DK	

1) Emissions at 8 % O$_2$
2) Outlet water temperature from exhaust gas exchanger from 80 – 60 ^{o}C
3) Unit: mg/m^3 at 5 % O$_2$

5.4.4 Fuel cells

The fuel cell works in principal as a battery. The main difference is that a fuel cell is continuously fed with a fuel and air/oxygen, while a battery is batchwise charged (Jannach, 2011). The main components in a fuel cell are:

- A cell including an anode, a cathode and an electrolyte. There are several cell techniques. Most cells use hydrogen as fuel and the hydrogen is fed to the anode. The air/oxygen is fed to the cathode. An electrochemical reaction takes place between the anode and the cathode generating an electric current. A fuel cell consists of numerous cells often called a stack. The anode has a catalyst for improving the electrochemical reaction.
- A reformer which is a pre-treatment step for the fuel (ex. natural gas, biogas) converting the fuel to hydrogen. There are several reforming techniques. Some cells can use other fuels than hydrogen (ex, methanol).

There are more than a dozen fuel cell types. Some typical characteristics for a few fuel cell types are described in Table 9.

According to Jannach (2011), the most frequently used fuel cell today is LT-PEMFC, but it has disadvantages, such as high quality fuel demand, and it needs a reformer, if the fuel is not hydrogen. The high temperature fuel cells SOFC and MCFC have advantages, such as lower demand on fuel quality and ability to use biogas without carbon dioxide separation. Due to the high temperature, the reforming of methane to hydrogen can also take place within the cell (internal reforming) without an external reformer, which makes the construction of the fuel cell less complex. A disadvantage with SOFC and MCFC fuel cells is that the operational experience from the technologies is currently limited.

Table 9. Characteristic figures for most common fuel cells technologies in which natural gas/biogas is used to feed the reformer (Jannach, 2011).

Cell technology[1]	LT-PEMFC	DMFC	HT-PEMFC	AFC	PAFC	MCFC	IT/HT-SOFC
Operating temperature (^{o}C)	60-90	60-90	120-180	50-250	150-200	600-700	550-650 / 700-900
Fuel [2]	H_2	H_2, methanol	H_2	H_2	H_2	H_2, CO, CH_4	H_2, CO, CH_4
Oxidation	Air	Air	Air	O_2	Air	Air + CO_2	Air
Tolerance towards gas impurities	Very low	Very low	Moderate	Extremely low	Moderate	Moderate	Moderate
Catalyst poison [2]	CO, S, NH_3	CO, S, NH_3	CO, S, NH_3	CO, S, NH_3, CH_4, CO_2	S	S	S
Electrical cell efficiency [3&4]	50-70	20-30	50-70	60-70	50-60	50-60	60-65

1) Cell technologies:
   - LT-PEMFC: Low Temperature Polymer-Electrolyte-Membrane Fuel Cell
   - DMFC: Direct Methanol Fuel Cell
   - HT-PEMFC: High Temperature Polymer-Electrolyte-Membrane Fuel Cell
   - AFC: Alkaline Fuel Cell
   - PAFC: Phosphoric Acid Fuel Cell
   - MCFC: Molten Carbonate Fuel Cell
   - IT/HT-SOFC: Intermediate Temperature/High Temperature Solid Oxide Fuel Cell
2) Catalyst poison:
   - H_2: Hydrogen
   - CO: Carbone monoxide
   - S: Sulphur
   - NH_3: Ammonia
   - CH_4: Methane
   - CO_2: Carbone dioxide
3) The cell efficiency is based on hydrogen as fuel (lower heating value for H_2). Internal process electricity demand is not included. Fuel cell efficiency also degrades with time.
4) Typical electrical system efficiency for the whole fuel cell including all internal process electricity and other system loses is 30-40% for most fuel cell technologies.

Low temperature fuel cells require precious metal catalysts and this increases the material cost. Furthermore, there are strict tolerances on fuel quality. Higher temperature systems, on the other hand, require a prolonged warm-up period. This makes it impractical to turn them on and off (Staffel, 2009) for intermittent operation.

According to Remick (2009), there are two manufactures in the US with a track record of supplying fuel cell power plants using biogas as fuel (Table 10).

Table 10. Example of commercial fuel cells from two US companies for CHP with biogas as fuel (Remick, 2009).

Company	Fuel Cell Energy	UTC Power	Unit
Technology	MCFC	PAFC	kW
Electrical output	1400	400	kW
Electrical efficiency	47	42	% LHV at beginning of life
System efficiency	Up to 74	Up to 85	%
Power plant life	20	20	Years
Overhaul	Every 5 year	Every 10 year	

The functional lifetime of fuel cells is a crucial and contentious issue for the commercialisation and economic viability of fuel cell micro-CHP systems. The industry target of 40,000 hours of continuous operation has so far only being attained in the field by industrial PAFC systems from UTC and Fuji (Staffell, 2009). Fuel cells are currently very expensive, but the fuel cell market is optimistic about the development of the technology due to rapidly falling prices, higher efficiency and more robust constructions.

5.4.5 *Waste heat utilisation*

5.4.5.1 *Organic Rankine Cycle*

With an Organic Rankine Cycle (ORC) unit, waste heat from a combined heat and power plant can be used for increasing the production of electricity. The usual working fluid for Rankine cycles is water under pressure used e.g. in electricity production at nuclear power plants and coal-based plants. The main components in a Rankine cycle are:

- A boiler (steam production at high pressure)
- A turbine (expansion of steam reducing the pressure, the turbine generates electricity)
- A condenser (converting steam to liquid)
- A pump (increasing the pressure in the liquid)

Using water as working fluid, it is important that the cycle has a high steam temperature, to get high efficiency converting the used fuel into electricity.

When using otto or diesel engine for heat and power production, the temperature of the waste heat (motor cooling or exhaust gases) is too low for using water as a working fluid in a Rankine process. Instead, hydrocarbons or refrigerants are used as the working fluid for this particular application. The physical properties of the working fluid are of key importance, influencing the efficiency of the Rankine cycle (Quoilin, 2007).

Quoilin (2007) reports the efficiency for an ORC process from both laboratory bench tests with working fluid R123 and modelling. In theory, 11.6% of the heat energy supplied to the evaporator could generate mechanical energy. In the laboratory test, the achieved mechanical energy was 2.7 - 7.4% of the heat energy supplied to the evaporator (Table 11). The heat source used for the evaporator had a temperature of 135 – 182 ^{o}C and the condenser was cooled by tap water.

Table 11. Efficiency for Organic Rankine Cycle in a laboratory test and in a computer model.

	Laboratory test	Modelling, cycle optimisation	Unit
Boiling temperature in evaporator	Approx. 100	100	^{o}C
Superheating temperature, inflow expander	102-168	42	^{o}C
Pressure ratio, expansion	2.7-5.4	-	
Cycle efficiency [1]	2.6 – 7.4	11.6	%
Carnot efficiency	27.7-36.4	-	%

1) Cycle efficiency: The ratio between net mechanical energy and heat transfer to the evaporator. Net mechanical energy is shaft power generated by the expander minus pump energy.

GE Jenbacher has developed a CHP unit in which the exhausted gases (approx. 450 ^{o}C) and heat from the motor cooling (approx. 90 ^{o}C) is used in ORC for increasing the electricity production. The GE Jenbacher ORC increased the electricity yield with 6% at a field test (17 000 h in operation) using two different fluids (Hillen et al., 2010b). The units estimated potential is in excess of 8% of increased electricity yield.

5.4.5.2 Sorption cooling

Waste heat from a CHP plant can be used for running a sorption cooling unit. For a farm with dairy cows, a sorption process can be used for cooling milk. The sorption processes can also be used for air conditioning and improving stable climate during summer.

Brown & Pettersson (2009) studied the prospect of using waste heat from a biogas fuelled CHP unit running a sorption process for cooling milk. In one case, a farm with 160 dairy cows, robotic milking and a sorption cooling system could reduce electricity consumption by approx. 9 MWh/yr compared to a conventional milk cooling system. This corresponds to 6.8% of the net electrical production from the CHP plant. The result from the study is based on the following assumptions:

- 470 MWh/a of biogas energy from digesting 3200 tonnes of liquid manure per year
- Electrical efficiency of the CHP 30%
- Motor cooling temperature 95 ^{o}C
- Ammonia as the working fluid in the sorption process
- Milk temperature after cooling +3 ^{o}C
- Monthly COP (Coefficient of Performance is the ratio between the heat transfer by evaporator and used waste heat running the process) variation for the sorption process varied between 0.22 and 0.3.

5.5 Biogas as vehicle fuel

According to Petersson & Wellinger (2009), the number of upgrading plants in operation was approx. 100 worldwide in 2009. About 40% of these were located in Sweden and 30% in Germany. In Sweden, there are 122 public filling stations for biogas and another 45 non-public filling stations for buses, garbage trucks etc. (Gyrulf, pers. com). The number of vehicles using biogas as fuel in Sweden in 2010 was:

- 30,100 cars
- 1,400 buses
- 500 trucks

In total, the quantity of biogas used as vehicle fuel In Sweden in 2010 was approx. 950 GWh/year (prognosis), of which biogas contributed approximately 600 GWh and natural gas 350 GWh (Gyrulf, pers. com.).

5.5.1 *Biogas standard for biomethane as fuel*

Sweden has developed a national standard for biogas as vehicle fuel to serve as a design basis for fuel and engine systems for biogas vehicles (Table 12).

To be able to use biogas as vehicle fuel, it has to be upgraded to attain the requirements in the standard SS 155438. In the upgrading plant, the following substances have to be controlled and, if required, removed:
- Carbon dioxide
- Water
- Hydrogen sulphide
- Oxygen
- Nitrogen
- Ammonia
- Siloxanes
- Particulates

Table 12. Extract from the Swedish standard SS 155438 "Motor fuels – Biogas as fuel for high-speed otto engines".

Parameter	Demand in standard	Unit
Methane	97 ± 2	%
Wobbe index$_{LHV}$	43.9-47.3	MJ/Nm^3
Motor Octan Number	130	
Particle size	< 1	µm
$CO_2 + O_2 + N_2$	<5	%
O_2	<1	%
H_2	<0.5	%
Water	< 32	g/Nm^3
Dewpoint at highest storage pressure	t – 5 [a)]	^{o}C
Total sulphur	< 23	g/Nm^3
H_2S	< 10	ppm
NH_3	< 20	g/Nm^3
Pressure	200	bars

a) t = lowest monthly daily average temperature
CO_2 = carbon dioxide; O_2 = oxygen; N_2 = nitrogen; H_2 = hydrogen; H_2S = hydrogen sulphide; NH_3 = ammonia

The upgraded biogas should also be odorised to enable the detection of the gas at a concentration of >20% of its flammability limit.

5.5.2   *Commercial upgrading plants for larger applications*

In the present report, upgrading of biogas is defined as removal of carbon dioxide from the gas. Three principally different technologies are on the market for upgrading biogas. They are briefly described in this chapter. The principle for the most common upgrading technique in Sweden, water scrubbing, is described in Fig. 13.
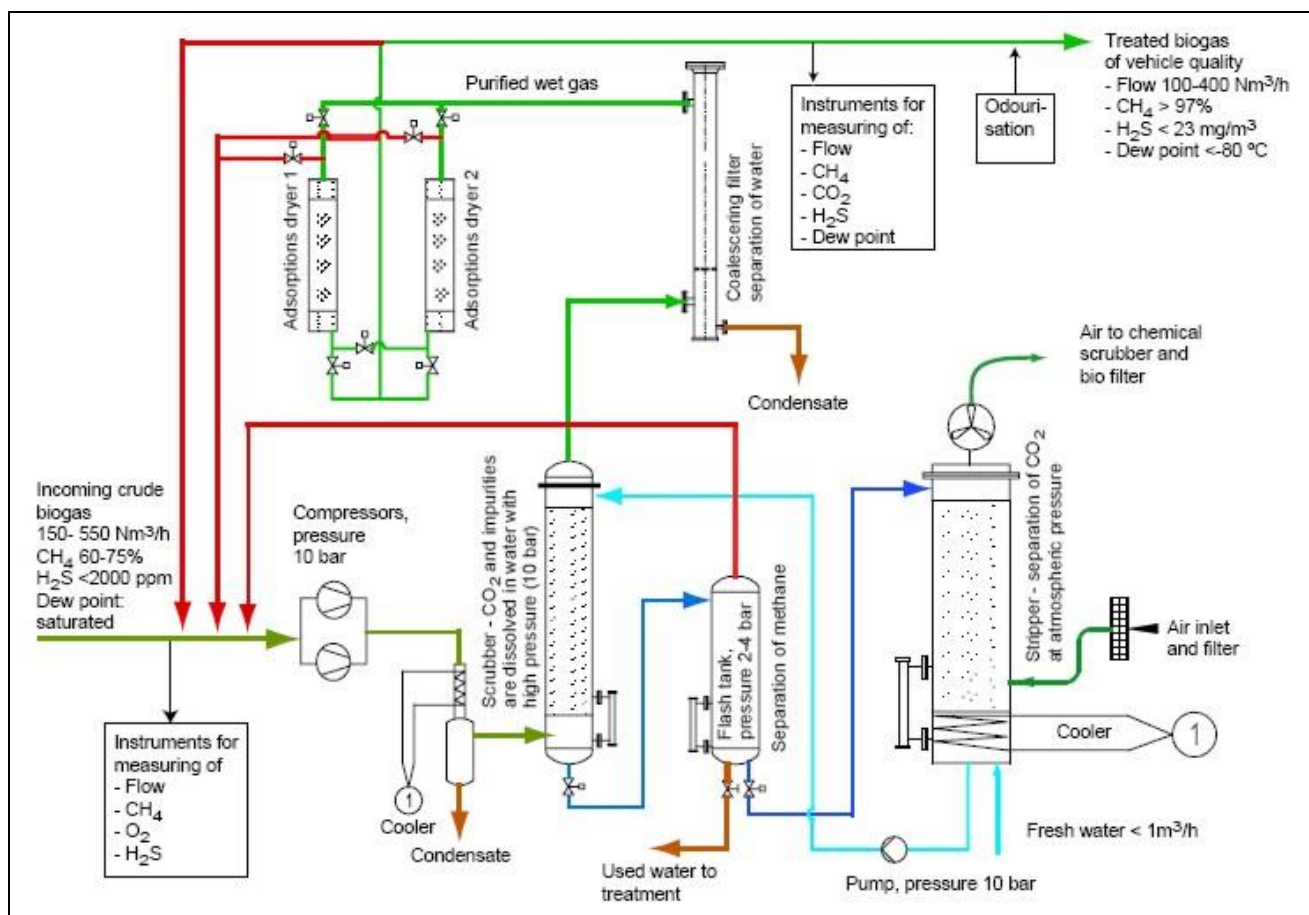

Figure 13. Principle description for biogas upgrading plant using water scrubbing technique (Weiland & Ahrens, 2006).

5.5.2.1   *Pressure Swing Adsoption (PSA)*

With this technology, carbon dioxide is separated from the biogas by adsorption on a surface (usually activated carbon or zeolites) under elevated pressure. The surface material will be saturated with carbon dioxide and must then be regenerated (Petersson & Wellinger, 2009). The electrical demand for one PSA plant is estimated at 0.05 kWh electricity/kWh upgraded biogas (RVF, 2005). This electricity demand is twice as high as that reported in Urban et al. (2009) for PSA plants. The number of PSA-plants in Sweden in 2010 was eight (Petersson, pers. com.).

5.5.2.2   *Absorption*

With this technology, the raw biogas meets a counter flow of a liquid in a high pressure column filled with plastic packing. The principal of the technology is that carbon dioxide is more soluble in

the liquid than methane. The carbon dioxide enriched liquid is pumped to a low pressure flushing column in which the carbon dioxide is released from the liquid (Figure 14).
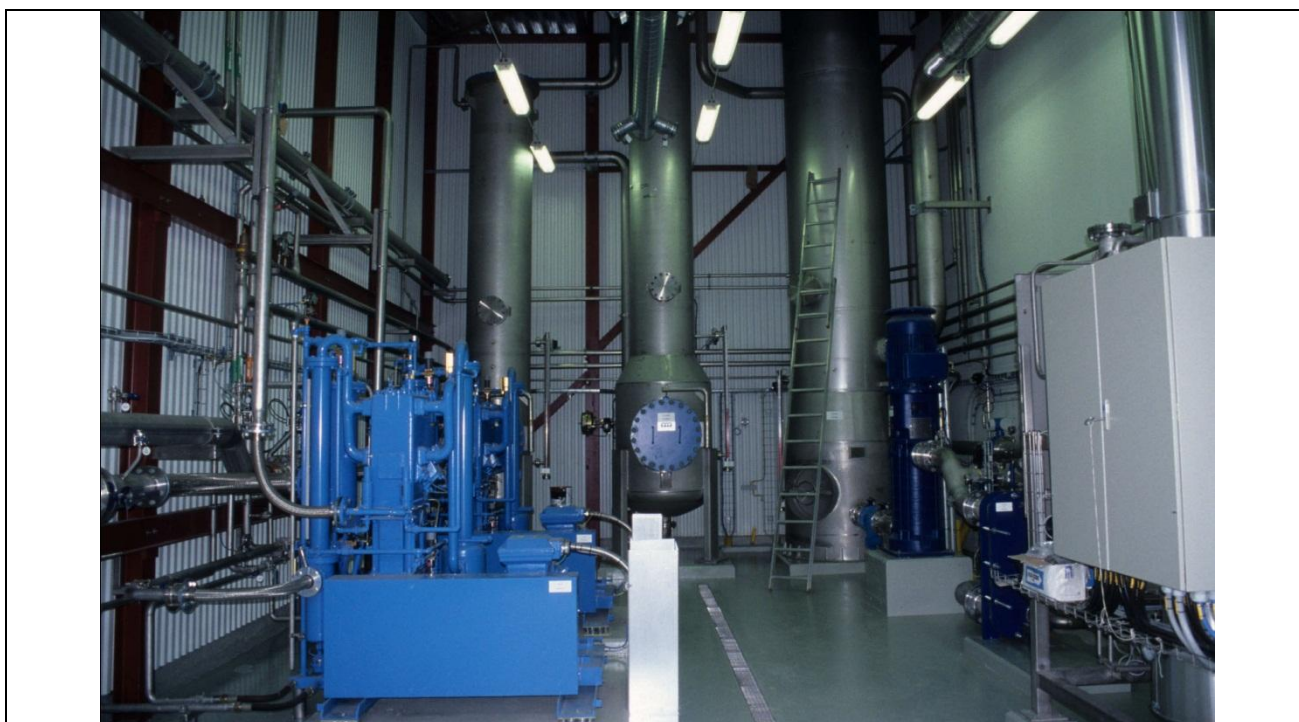

Figure 14. An absorption biogas upgrading plant using water as absorption media.The plant includes following main columns (see also figure Ux): The water scrubber (the column in the middle in behind), the flash tank (the left column) and the stripper column (the right column). The untreated biogas is fed into the water scrubber column. The pressure in this column is 10 – 12 bars (the blue machine on the left is compressor for increase the pressure to 12 bars). Carbon dioxide and other impurities are absorbed in the water. Most of the methane is collected at the top of the water scrubber column but some methane is dissolved in the water. After the scrubber the process water is led to the flash tank. In the flash tank the pressure is reduced to 2-4 bar in order to recover dissolved methane in the water and thereby reduce the losses of methane from the plant. The collected gas from the flash tank is led back to the inlet of the water scrubber column. The used process water is regenerated in the stripper column. Degassing of carbon dioxide and hydrogen sulphide is done at atmospheric pressure with air that is blown through the column. Photo: Mats Edström, JTI.

Water scrubbing

Water is used as absorption media in water scrubbing which is the most common upgrading technology (Petersson & Wellinger, 2009). The electrical demand for the water scrubber has been measured at four plants to be 0.03-0.06 kWh electricity/kWh upgraded biogas (RVF, 2005). Weiland & Ahrens (2006) report an electrical demand for an evaluated water scrubber (capacity: 550 Nm^3 untreated biogas/h) to be 0.048 kWh electricity/kWh upgraded biogas at maximum plant capacity. These electricity demands are significantly higher than the <0.025 kWh electricity/kWh upgraded biogas reported by Urban et al. (2009) for water scrubbing plants and including electricity demand for transporting the upgraded biogas in a 8.5 km long pipe at maximum 4 bar pressure. The number of water scrubbing plants in Sweden in 2010 was 33 (Petersson, pers. com.).

Organic physical scrubbing

An organic solvent, such as polyethylene glycol, can also be used as an absorption media. Carbon dioxide is more soluble in the solvent than to water, resulting in a lower liquid flow and thus, a smaller plant (Petersson & Wellinger, 2009). The electrical demand for the organic physical scrubber is reported to be 0.024 – 0.03 kWh electricity/kWh upgraded biogas (Urban et al., 2009).

Chemical scrubbing

Amine solution is another possible absorption media as carbon dioxide reacts chemically with the amine in the liquid. This technology results in very low methane losses (Petersson & Wellinger, 2009). The electrical demand for the chemical scrubber is stated by a manufacture to be 0.015 kWh electricity/kWh upgraded biogas (RVF, 2005). To release the carbon dioxide in the stripper column, the amine solution has to be heated to 160 $^{\circ}$C (Urban et al., 2009) in order to be regenerated. The heat can be recovered and used in the biogas plant for process heating. The heat demand for regeneration has been calculated as 0.048 kWh heat/kWh biogas (Hermansson, 2009).

The number of chemical and organic physical scrubbing plants in Sweden in 2010 was six (Petersson, pers. com.).

5.5.2.3 Membranes

Dry membranes can be used for upgrading biogas although this is not a common technology. The membrane is permeable to carbon dioxide, water and ammonia and to some extent to hydrogen sulphide and oxygen, while in a very low extent permeable to methane and nitrogen (Petersson & Wellinger, 2009).

5.5.3 Emerging technologies

Cryogenic upgrading makes use of the different boiling/sublimation points of different gases to separate carbon dioxide from methane (Petersson & Wellinger, 2009). The electrical demand for three different cryogenic upgrading systems is reported to be 0.023 – 0.031 kWh electricity/kWh upgraded biogas (Hermansson, 2009) and the heat demand of the same systems were 0 – 0.026 kWh heat/kWh upgraded biogas. The number of cryogenic upgrading plants in Sweden in 2010 is two (Pettersson, pers. com.). The technology is in a testing phase in Sweden.

Enzymes are used to first convert carbon dioxide into carbonate, while in the second step, a reverse reaction occurs, converting carbonate back to carbon dioxide in an "ecological lung".

In situ methane enrichment makes use of the fact that in the digester sludge, carbon dioxide can be found as dissolved carbon dioxide and as carbonate. Sludge from the digester is pumped into a desorption column in which it is aerated, resulting in dissolved carbon (but also, to some extent, carbonate is converted to dissolved carbon dioxide and then desorbed) leaving the sludge with the air. The sludge leaving the desorption column, which has a low content of dissolved carbon dioxide, is then pumped back into the digester. The methane enrichment process can result in an increase in the methane concentration to above 90% in the biogas leaving the digester.

5.5.4 Methane emissions

Methane is a strong greenhouse gas. Thus, it is important to minimise methane emissions connected to biogas upgrading. Usually 2% of loss is considered acceptable. In Sweden, there is a voluntary system for control of methane emissions. This includes an inventory of emissions, setting of plant-specific targets for emissions and monitoring of fulfillment of the targets set. The pioneer methane emissions measurements connected to biogas upgrading resulted in (Holmgren, pers. com.):

- Water scrubber plants, 1.2-4.2 % methane losses
- Chemical scrubbing plants, 0.1-0.6 % methane losses
- PSA plants, 1.1-3.7% methane losses

The voluntary system has in general resulted in substantial reductions in biogas upgrading plants with high methane emissions.

5.5.5 Distribution and filling

In most countries using upgrading technologies, injection to the natural gas grid is the common market for the upgraded biogas. In Sweden, the situation is different due do the limited area covered by the gas grid system. Thus, most of the upgraded biogas in Sweden is sold directly to the vehicle market close to the upgrading plant. This has also resulted in technologies for truck transportation of compressed biogas in short- and mid-range distances to enlarge the vehicle fuel market. There is also a momentum in Sweden to develop technologies for producing LBG (liquid biogas) in order to make the distribution of biogas as vehicle fuel more efficient.

After upgrading, the biogas fuel has to be compressed (or liquefied) before fuelling a vehicle tank to a pressure of 200 bar. The amount of energy stored in compressed gas is significantly less than the energy stored in the same volume of liquid fuel as petrol or diesel (the energy content per tank volume of fuel biogas is about 20% of the energy per volume of petrol). Therefore, the operating range for a compressed biogas fuel vehicle is reduced compared with a petrol car or a diesel bus.

There are two basic methods of fuelling compressed biogas fuel to vehicles: slow-fill and fast-fill. Slow-fill systems take gas directly from the compressor into the vehicle. Refuelling time for a large vehicle can take a couple of hours and these systems are only suitable when sufficient refuelling time is available outside the hours of operation (example: bus overnight). Fast-fill systems using cascade fuel storage tanks (Figure 15) can refuel vehicles in about the same time or only slightly longer than in normal liquid fuel vehicles.

Figure 15. High pressure storage for fast filling of biogas vehicle. Each steel tube has 2000 liters volume and the maximum gas pressure in a tube is 350 bar. Photo: Mats Edström, JTI.

The electrical demand for compressing the upgraded biogas to fuel a vehicle was measured at four plants and reported to be 0.015-0.042 kWh electricity/kWh upgraded biogas (RVF, 2005). Weiland & Ahrens (2006) reports that electrical demand for compressing upgraded biogas is 0.024 kWh electricity/kWh upgraded biogas.

6   Use of digestate

In this report only some basic matters related to digestate use are touched upon. Other work packages in the project Baltic MANURE will be reporting more on the issue (www.balticmanure.eu).

Digested manure is more homogeneous than raw manure due to the degradation of solid materials (TS). The content of organic matter (VS) is also lower making the digestate biologically more stabilised than raw manure. As the organic compounds are degraded, but the nitrogen content remains the same, the ratio of carbon and nitrogen is more suitable for fertilising purposes in digestate than in raw manure. A higher amount of total nitrogen is present as soluble and readily-available ammonium for plants, further increasing the fertilising value of the digestate. The addition of co-substrates usually improves the fertiliser value further. Especially co-digestion of crops and manure produce a better phosphorous to nitrogen ratio in the digestate than digesting manure alone, as 50-85% of the total nitrogen in crops is converted to ammonium during the process (compared to 20-30% of manure alone).

As the biogas process degrades compounds causing foul odours, the use of the digestate is more acceptable also in the vicinity of settlements than that of raw manure. Additionally, the biogas process destroys pathogens, the degree of destruction depending on process temperature: the higher the temperature, the more significant the hygienisation. The digestate quality is further improved due to degradation/destruction of vermin, weed seeds and some hazardous compounds, such as phthalates and polyaromatic hydrocarbons (PAH).

6.1 Storage

Digestate should be stored in covered storage tanks to minimise ammonia evaporation. As the ammonium content and pH of the digestate is higher than e.g. in raw manure, more ammonia is present and susceptible for evaporation. The higher the temperature in the storage, the higher is the risk for nitrogen loss as ammonia. This is not only unwanted due to fertiliser value of nitrogen, but also due to the harmful environmental effects of ammonia.

In a Finnish study, life cycle assessment of different manure management scenarios showed that ammonia evaporation and the resulting acidifying effects on the environment were the most significant environmental hazard from manure. With respect to biogas use, the risk was even more prominent than with raw manure due to the higher pH and ammonium content of digestate (Grönroos et al., 2011). According to Amon et al. (2006a; 2006b), ammonia emissions from digestate originate mostly from field application (96%), while with raw manure more ammonia is emitted from storage tanks. Moreover, covered digestate storage decreased the emissions from digestate storage tank by 65% as opposed to open storage.

Covered storages also reduce the methane emissions from the digestate as described in the chapter dealing with post-digestion (see chapter 4.4.1.). It also serves as elimination of unwanted dilution from e.g. rain water.

6.2 Fertiliser use

The digestate from typical manure-based biogas plants is a sludge which can be spread as such on fields using the same machinery as with liquid manure. Injection into the soil, or at least instantaneous mulching, is recommended in order to i) direct the nutrients where they are needed, i.e. in the root zone of the crops, ii) minimise ammonia evaporation, and iii) reduce nutrient run-off. It is also advisable to spread the digestate only on vegetative phase in order to efficiently use it as fertiliser and minimise harmful emissions. The recommendations are the same whether spreading digestate as such or as mechanically separated fractions.

More targeted fertiliser products can also be produced via inclusion of other technological processes after the digestion (see chapter 4.4.). Possible technologies include mechanical separation, pelletising, ammonia stripping, evaporation, phosphorus crystallization, just to mention a few. The products from these process chains may closely resemble inorganic fertilisers as they usually aim at separating and concentrating the nutrient of digestates. Examples of such products include e.g. ammonia water and ammonium sulphate.

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Map of the Baltic Sea Region showing: Sweden, Finland, Norway, Estonia, Latvia, Lithuania, Denmark, Poland, Germany, and The Baltic Sea.

This report in brief

Manure based biogas is well known technology. Interest in biogas technology is increasing around the world due to the requirements for renewable energy production, reuse of materials and reduction of harmful emissions. This report is an overview of biogas technologies with the aim of introducing them in a simple, easy-to-read way, including pre- and post treatment of the manure to achieve the mentioned targets.

The methane-rich biogas can be utilized as renewable energy in various ways as described in this report. In addition, the residual material, the digestate, contains all the nutrients of the original raw materials and offers a way to recycle them.

Biogas technology is currently the most sustainable way to utilise the energy content of manure while also recycling the nutrients and minimizing the emissions.

This report on manure based biogas was prepared as part of Workpackage 6 on Manure Energy Potentials in the project Baltic Manure.

About the project

The Baltic Sea Region is an area of intensive agricultural production. Animal manure is often considered to be a waste product and an environmental problem.

The long-term strategic objective of the project Baltic Manure is to change the general perception of manure from a waste product to a resource. This is done through research and by identifying inherent business opportunities with the proper manure handling technologies and policy framework.

To achieve this objective, three interconnected manure forums has been established with the focus areas of Knowledge, Policy and Business.

Read more at www.balticmanure.eu.

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