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Methane production by anaerobic digestion of wastewater and solid wastes

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Abstract

Anaerobic digestion is an established technology for the treatment of wastes and wastewater. The final product is biogas: a mixture of methane (55-75 vol%) and carbon dioxide (25-45 vol%) that can be used for heating, upgrading to natural gas quality or co-generation of electricity and heat. Digestion installations are technologically simple with low energy and space requirements. Anaerobic treatment systems are divided into 'high-rate' systems involving biomass retention and 'low-rate' systems without biomass retention. High-rate systems are characterised by a relatively short hydraulic retention time but long sludge retention time and can be used to treat many types of wastewater. Low-rate systems are generally used to digest slurries and solid wastes and are characterised by a long hydraulic retention time, equal to the sludge retention time. The biogas yield varies with the type and concentration of the feedstock and process conditions. For the organic fraction of municipal solid waste and animal manure biogas yields of 80-200 m^3 per tonne and 2-45 m^3 per m^3 are reported, respectively. Co-digestion is an important factor for improving reactor efficiency and economic feasibility. In The Netherlands co-digestion is only allowed for a limited range of substrates, due to legislation on the use of digested substrate in agriculture. Maximising the sale of all usable co-products will improve the economic merits of anaerobic treatment. Furthermore, financial incentives for renewable energy production will enhance the competitiveness of anaerobic digestion versus aerobic composting. Anaerobic digestion systems currently operational in Europe have a total capacity of 1,500 MW, while the potential deployment in 2010 is estimated at 5,300-6,300 MW. Worldwide a capacity up to 20,000 MW could be realised by 2010. Environmental pressures to improve waste management and production of sustainable energy as well as improving the technology's economics will contribute to broader application.

4.1 Introduction

Anaerobic conversion of organic materials and pollutants is an established technology for environmental protection through the treatment of wastes and wastewater. The end product is biogas –a mixture of methane and carbon dioxide–, which is a useful, renewable energy source. Anaerobic digestion is a technologically simple process, with a low energy requirement, used to convert organic material from a wide range of wastewater types, solid wastes and biomass into methane. A much wider application of the technology is desirable in the current endeavours towards sustainable development and renewable energy production. In the 1980's several projects were initiated in The Netherlands to produce biogas from wastes. Many projects were terminated due to insufficient economic viability. Currently, the production of methane from wastes is receiving renewed attention as it can potentially reduce CO_2 emissions via the production of renewable energy and limit the emission of the greenhouse gas methane from especially animal manure. This trend is supported by the growing market demand for 'green' energy and by the substantial optimisation of anaerobic digestion technologies in the past decades, especially the development of modern 'high rate' and co-digestion systems.

The aim of this chapter is to review and evaluate the various anaerobic digestion technologies to establish their potential for methane production, aimed at broadening the range of waste streams

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used for biogas production. The principles of anaerobic digestion are outlined in Section 4.2. In Section 4.3 anaerobic digestion technologies and their application for specific waste streams are discussed. An overview of solid wastes and wastewater streams available for anaerobic digestion in The Netherlands is presented in Section 4.4. In Section 4.5 the utilisation of biogas as a renewable energy source is highlighted, including the current and potential share of bio-methane in The Netherlands. The economics of anaerobic digestion are discussed in Section 4.6. The status of international developments is presented in Section 4.7. Conclusions and perspectives for further development are presented in Section 4.8.

4.2 Basic principles of anaerobic digestion

4.2.1 Principle of the process

Anaerobic microbiological decomposition is a process in which micro-organisms derive energy and grow by metabolising organic material in an oxygen-free environment resulting in the production of methane (CH_4). The anaerobic digestion process can be subdivided into the following four phases, each requiring its own characteristic group of micro-organisms:

- Hydrolysis: conversion of non-soluble biopolymers to soluble organic compounds
- Acidogenesis: conversion of soluble organic compounds to volatile fatty acids (VFA) and CO_2
- Acetogenesis: conversion of volatile fatty acids to acetate and H_2
- Methanogenesis: conversion of acetate and CO_2 plus H_2 to methane gas

A simplified schematic representation of anaerobic degradation of organic matter is given as Figure 1. The acidogenic bacteria excrete enzymes for hydrolysis and convert soluble organics to volatile fatty acids and alcohols. Volatile fatty acids and alcohols are then converted by acetogenic bacteria into acetic acid or hydrogen and carbon dioxide. Methanogenic bacteria then use acetic acid or hydrogen and carbon dioxide to produce methane.

For stable digestion to proceed it is vital that various biological conversions remain sufficiently coupled during the process, to prevent the accumulation of intermediate compounds. For example, an accumulation of volatile fatty acids will result in a decrease of pH under which conditions methanogenesis cannot occur anymore, which

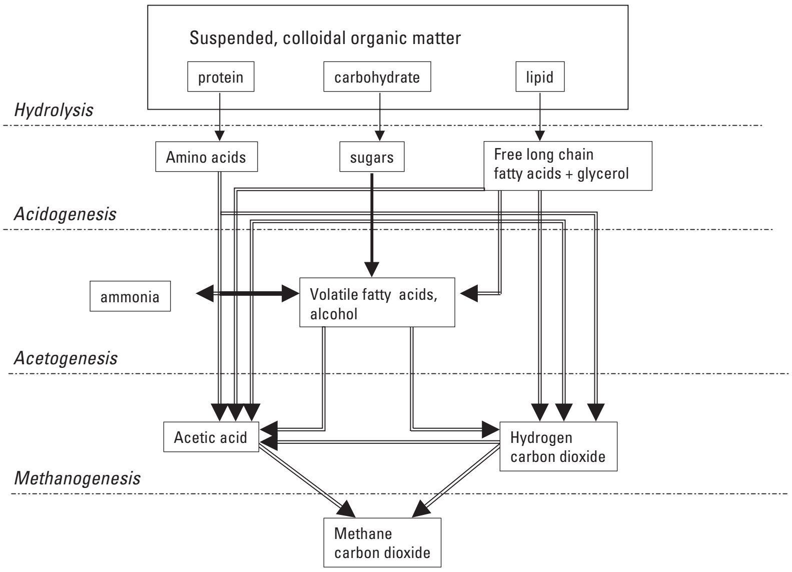


Figure 1. Simplified schematic representation of the anaerobic degradation process [1].

results in a further decrease of pH. If hydrogen pressure becomes too high, further reduced volatile fatty acids are formed, which again results in a decrease of pH.

4.2.2 Environmental factors affecting anaerobic digestion

As anaerobic digestion is a biological process, it is strongly influenced by environmental factors. Temperature, pH and alkalinity and toxicity are primary control factors.

Controlled digestion is divided in psychrophilic (10-20 °C), mesophilic (20-40 °C), or thermophilic (50-60 °C) digestion. As bacterial growth and conversion processes are slower under low temperature conditions, psychrophilic digestion requires a long retention time, resulting in large reactor volumes. Mesophilic digestion requires less reactor volume. Thermophilic digestion is especially suited when the waste(water) is discharged at a high temperature or when pathogen removal is an important issue. During thermophilic treatment high loading rates can be applied. Anaerobic digestion can occur at temperatures as low as 0°C, but the rate of methane production increases with increasing temperature until a relative maximum is reached at 35 to 37° C [2]. At this temperature range mesophilic organisms are involved. The relation between energy requirement and biogas yield will further determine the choice of temperature. At higher temperatures, thermophilic bacteria replace mesophilic bacteria and a maximum methanogenic activity occurs at about 55°C or higher.

The first steps of anaerobic digestion can occur at a wide range of pH values, while methanogenesis only proceeds when the pH is neutral [2]. For pH values outside the range 6.5 - 7.5, the rate of methane production is lower. A sufficient amount of hydrogen carbonate (frequently denoted as bicarbonate alkalinity) in the solution is important to maintain the optimal pH range required for methanogenesis.

Several compounds exhibit a toxic effect at excessive concentrations such as VFA's, ammonia, cations such as Na^+, K^+ and Ca^{++}, heavy metals, sulphide and xenobiotics, which adversely affect methanogenesis.

4.2.3 Methane production potential

The Chemical Oxygen Demand (COD) is used to quantify the amount of organic matter in waste streams and predict the potential for biogas production. The oxygen equivalent of organic matter that can be oxidised, is measured using a strong chemical oxidising agent in an acidic medium.

During anaerobic digestion the biodegradable COD present in organic material is preserved in the end products, namely methane and the newly formed bacterial mass.

In case an organic compound ($C_nH_aO_bN_d$) is completely biodegradable and would be completely converted by the anaerobic organism (sludge yield is assumed to be zero) into CH_4, CO_2 and NH_3, the theoretical amount of the gases produced can be calculated according to the Buswell equation (1):

$$C_nH_aO_bN_d + (n-a/4 - b/2 + 3d/4)\ H_2O \rightarrow$$
$$(n/2 + a/8 - b/4 - 3d/8)\ CH_4 +$$
$$(n/2 - a/8 + b/4 + 3d/8)\ CO_2 + dNH_3 \qquad \text{(equation 1)}$$

The quantity of CO_2 present in the biogas generally is significantly lower than follows from the Buswell equation. This is because of a relatively high solubility of CO_2 in water and part of the CO_2 may become chemically bound in the water phase.

Another widely used parameter of organic pollution is the Biological Oxygen Demand (BOD). This method involves the measurement of dissolved oxygen used by aerobic microorganisms in biochemical oxidation of organic matter during 5 days at 20 °C.

A very useful parameter to evaluate substrates for anaerobic digestion is the anaerobic biodegradability and hydrolysis constant [3]. The total anaerobic biodegradability is measured by the total amount of methane produced during a retention time of at least 50 days.

The gas yield depends on factors such as digestibility of the organic matter, digestion kinetics, the retention time in the digester and the digestion temperature. By controlling conditions such as temperature, humidity, microbial activity and waste properties, the process can be optimised.

4.2.4 Requirements for anaerobic digestion

Unlike aerobic wastewater treatment systems, the loading rate of anaerobic reactors is not limited by the supply of a reagent, but by the processing capacity of the microorganisms. Therefore, it is important that a sufficiently large bacterial mass is retained in the reactor. For low rate systems the latter is achieved by applying a sufficiently long retention time. For high rate systems the retention of biomass is increased in comparison with the retention of the liquid. The following conditions are essential for high rate anaerobic reactors [2]:

- A high concentration of anaerobic bacterial sludge must be retained under high organic (>10 kg/m^3/day) and high hydraulic (>10 m^3/m^3/day) loading conditions.
- Maximum contact must occur between the incoming feedstock and the bacterial mass.
- Also minimal transport problems should be experienced with respect to substrate compounds, intermediate and end products.

The base for design of anaerobic digestion systems is the slowest step during digestion, which is usually the conversion of biodegradable non-dissolved organic solids into soluble compounds. This process is described as hydrolysis, and is temperature dependent.

Sludge Retention Time (SRT) is an important parameter. When too short, methanogenesis will not occur [4], and the reactor will acidify as a result. An SRT of at least 15 days is necessary to ensure both methanogenesis, sufficient hydrolysis and acidification of lipids at 25 °C [4]. At lower temperature the SRT should be longer, as the growth rate of methanogens and the hydrolysis constant decrease with temperature. To ensure the same effluent standards, the SRT should be increased. In completely mixed systems, the SRT is equal to the HRT, while in systems with inbuilt sludge retention, the SRT is higher than the HRT. For the particular Upflow Anaerobic Sludge Bed (UASB) system, the required reactor volume ensuring a sufficient SRT is calculated according to equation 2. This equation is applied for wastewater with a high concentration of suspended solids, and for systems that are not hydraulically limited [5]:

$$HRT = \left(\frac{COD_{SSin}}{X}\right) * R * (1-H) * SRT \qquad \text{(equation 2)}$$

in which:

COD_{SSin} = COD of suspended solids in the influent (g/l)

X = sludge concentration in the reactor (g VSS/l); (1 g VSS=1.4 g COD)

R = fraction of the COD_{SS} removed

H = fraction of the removed COD_{SS}, which is hydrolysed at the imposed SRT

4.2.5 Advantages and disadvantages of anaerobic treatment

Advantages of anaerobic treatment are numerous and can be summarised as follows [1,6]:

- provision of energy source through methane recovery;
- anaerobic treatment processes generally consume little energy. At ambient temperature the energy requirements are in the range 0.05-0.1 kWh/m^3 (0.18-0.36 MJ/m^3), depending on the need for pumping and recycling effluent;
- reduction of solids to be handled; excess sludge production on the basis of biodegradable COD in anaerobic treatment is significantly lower compared to aerobic processes;
- facilitation of sludge dewatering;
- raw waste stabilisation;
- relatively odour free end-product;
- almost complete retention of the fertiliser nutrients nitrogen (N), phosphate (P) and potassium (K);
- modern anaerobic treatment processes can handle very high loads, exceeding values of 30 g COD/l/day at ca. 30 °C and up to 50 g COD/l/day at ca. 40 °C for medium strength mainly soluble wastewater;
- anaerobic sludge can be preserved for prolonged periods without any feeding;
- the construction costs are relatively low;
- the space requirements of anaerobic treatment are lower than conventional systems.

During anaerobic treatment biodegradable compounds are effectively removed, leaving a number of reduced compounds in the effluent, as well as ammonium, organic N-compounds, sulphide, organic P-compounds and pathogens. Depending on the further use a complementary treatment step is needed.

The disadvantages of anaerobic treatment are summarised below [1]:

- the high sensitivity of methanogenic bacteria to a large number of chemical compounds. In many cases anaerobic organisms are capable of adapting to these compounds;
- the first start-up of an installation without the presence of proper seed sludge can be time-consuming due to the low growth yield of anaerobic bacteria;
- when treating waste (water) containing sulphurous compounds, the anaerobic treatment can be accompanied by odour due to the formation of sulphide. An effective solution to this problem is to employ a micro-aerophilic post-treatment step, to convert sulphide to elemental sulphur.

4.3 The technology of anaerobic digestion

Anaerobic treatment is divided in 'low rate' systems, in which long hydraulic retention times are applied, and 'high rate' systems, in which hydraulic retention time is relatively short. Low rate systems are mainly used for waste streams such as slurries and solid waste, which require a long time for sufficient anaerobic degradation. High rate systems are mainly used for wastewater. The retention time of sludge in a low rate system is equal to the hydraulic retention time. In high rate systems however, the sludge retention time should be much higher than the hydraulic retention time. In essence, all high-rate processes have a mechanism either to retain bacterial sludge mass in the reactor or to separate bacterial sludge from the effluent and return it to the reactor. High rate systems are divided in two categories:

1) systems with fixed bacterial films on solid surfaces;
2) systems with a suspended bacterial mass where retention is achieved through external or internal settling.

Examples of low rate systems are: Batch, Accumulation, Plug flow and Continuously Stirred Tank Reactor (CSTR) systems. Examples of high rate systems are: Contact Process, Anaerobic Filter, Fluidised Bed and Upflow Anaerobic Sludge Bed (UASB) / Expanded Granular Sludge Bed (EGSB) [7].

4.3.1 Systems for treatment of solid waste and slurries

Systems used to digest solid waste are classified according to the percentage of Total Solids (TS) in the waste stream [8]:

15-25%	low solids anaerobic digestion: wet fermentation;
>30%	high solids anaerobic digestion: dry fermentation.

Figure 2 shows a schematic overview of digestion systems for slurries and solid wastes. Examples of existing plants are also shown, the processes of which are discussed later in detail.

During wet fermentation, slurry is digested; so the techniques for digestion of solid waste during wet fermentation and the digestion of slurries are comparable. Most digesters comprise a single reactor vessel (one phase system), but it is also possible to split microbial digestion into two phases, which can be operated in separate reactor vessels. Many types of reactors have been developed, based on the processes described above for the treatment of different types of wastes. They can be broadly categorised as low-solids, high-solids and multi-stage systems.

Plants used to treat organic solid waste are listed in Appendix I. This highlights the development of the technology and only includes plants processing more than 2,500 tonnes of slurry or solid waste per year. Appendix I includes wet fermentation and dry fermentation principles, both are discussed in the following sections and the techniques most commonly used are explained.

4.3.1.1 Wet fermentation systems

The most common form of low-solids reactor is the Continuously Stirred Tank Reactor (CSTR). Feed is introduced into the reactor, which is stirred continuously to ensure complete mixing of the reactor contents. At the same time an equal quantity of effluent is removed from the reactor. Retention time within the reactor can be varied according to the nature of the feedstock and process temperature applied, which is typically in the range of 2 - 4 weeks. Such systems have a low operating expenditure [8].

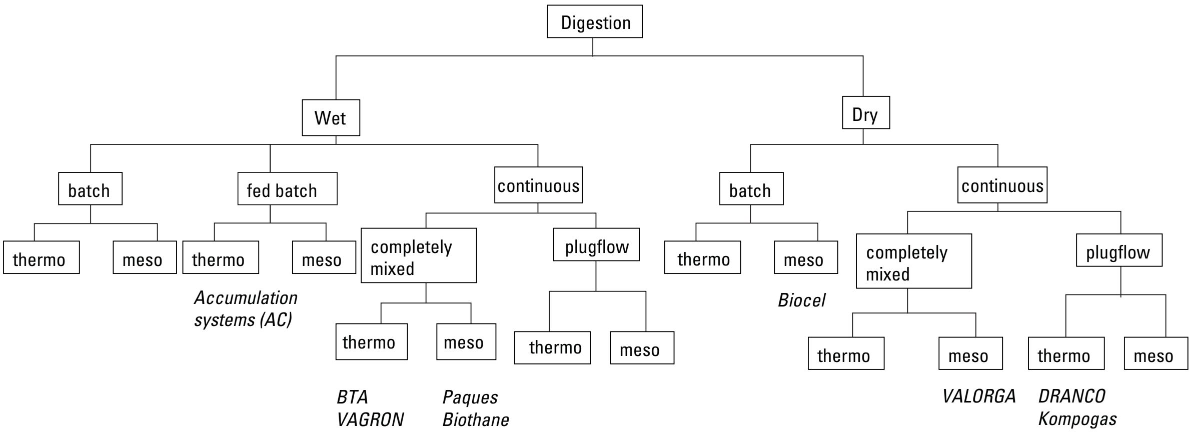


Figure 2. Schematic overview of digestion systems for slurries and solid waste. Commercial plants are indicated in italics.

The CSTR is generally used for treatment of slurries with a TS percentage of approximately 2-10%. The influent concentration range applicable for CSTR's is determined by:

- gas yield in relation to the energy requirement for heating;
- possibility of mixing the reactor content.

CSTR systems are applied in practice for treating animal manure, sewage sludge, household waste, agricultural wastes, faeces, urine and kitchen waste or mixtures of these substrates.
Mixing creates a homogeneous substrate, preventing stratification and formation of a surface crust, and ensures solids remain in suspension. Bacteria, substrates and liquid consequently have an equal retention time resulting in SRT is equal to HRT.

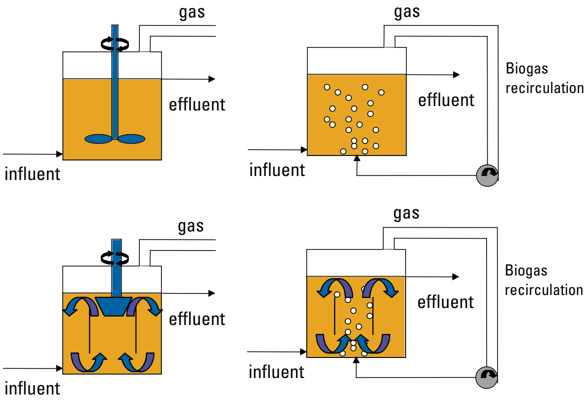


Figure 3. Schematic diagram of a CSTR system, mechanically stirred (top) and stirred by biogas recirculation (bottom) [10].

Digester volume ranges from around 100 m^3 to several thousand cubic metres, often with retention times of 10-20 days, resulting in daily capacities of 6 m^3 to 400 m^3 [9]. Examples of CSTR digesters with different mixing and heating systems are shown in Figure 3.

Plug-flow digesters use slurries, e.g. almost undiluted manure and have a total suspended solids concentration of 10-12% TS [11]. The basic digester design is a long trough (Figure 4), often built below ground level with a gas tight but expandable cover. At low TS concentration problems with floating and settling layers can appear [12]. This problem can be solved using vertical mixing inside the pipe. In this particular process, anaerobic stages such as hydrolysis and methanogenesis are separated over the length of the pipe. At first, hydrolysis mainly occurs, whereas later in the process methanogenesis takes place at full velocity. Using this system, the SRT is equal to the HRT. These systems are frequently used to treat slurries with a high fraction of suspended solids, as the hydrolysis of particulate matter is rate-limiting [3] hence only low loading rates can be applied.

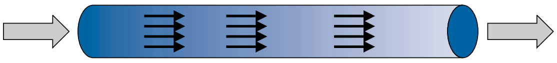


Figure 4. Schematic diagram of a plug flow digester.

In a batch system (Figure 5) the digester is filled at the start of the process. A disadvantage of the system is that a separate influent tank and effluent tank are needed. Batch systems are used as high-solids systems resulting in an equal SRT and HRT. It is advisable to leave approximately 15% of the contents to speed up the start-up of the process. In a batch system, treating mainly suspended solids, the different processes like hydrolysis, acidification and methanogenesis will not occur at the same rate. At first, time is needed to bring the suspended solids into a soluble form before it can be converted further to methane. The balance between the different processes at the start-up will depend on the percentage of inoculum applied. For solid waste digestion, liquid recirculation is applied to ensure sufficient contact between bacterial biomass and substrate.

Instead of a separate storage tank for the effluent, a combination of digestion and storage can be achieved in one tank. An **Accumulation System (AC)** is continuously fed and characterised by an increasing effective reactor volume with time. The reactor is almost completely emptied leaving 10-15% as inoculum. This system is the simplest system for on-site application of slurry digestion. A further facility, to normal storage consists of equipment for collection and use of the produced biogas and equipment is needed to optimise the process temperature, such as isolation and/or heating. The use of an AC-system is suitable when long-term storage is required. This type of system is mainly used on farms for the storage/digestion of manure, and is also used to digest faeces and urine in DeSaR (Decentralised Sanitation and Re-Use) systems [13]. The AC-system has also been tested on a small scale for solid manure digestion at thermophilic conditions for on-site energy production.

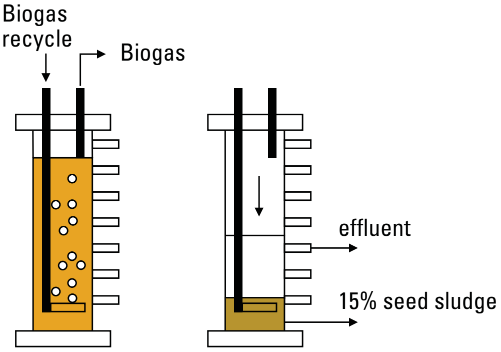


Figure 5. Schematic diagram of a batch reactor.

Wet digestion also has been carried out in a number of commercial and pilot-scale plants:

- AVECON or Waasa process, Vaasa, Finland [14], [15];
- VAGRON, Groningen, The Netherlands [16] named CiTech in Appendix I;
- Bigadan process, Denmark and Sweden [17], [18].

There are four **AVECON process** plants in Europe (one under construction), that can treat 3,000 - 85,000 tonnes per annum. The process can be operated at both thermophilic and mesophilic temperatures; the plant at Vaasa operates both systems in parallel. The thermophilic process has a retention time of 10 days compared to 20 days in the mesophilic process. The process has been tested on a number of waste types including a mixture of mechanically separated municipal solid waste/sewage sludge and operates in a solids range of 10-15%. The reactor is a single vessel, which is sub-divided internally to provide a pre-digestion chamber. Pumping biogas through the base of the reactor carries out mixing. The operational performance indicates that gas production is in the range 100-150 m^3/tonne of bio-waste added, with a volume reduction of 60%, weight reduction 50-60% and a 20-30% internal consumption of biogas. Aerobic composting, dependent on waste quality, can be used for post-treatment of the digested material.

At the **VAGRON plant** in Groningen (see Figure 11) the organic residual fraction is separated mechanically from the municipal solid waste stream and digested. At VAGRON, the temperature in the fermentation tanks is approximately 55 °C, resulting in thermophilic fermentation. The washed Organic Waste Fraction (OWF) remains in the tank for approximately 18 days, during which time approximately 60% of the organic material is converted into methane producing a total of 125 m^3 of biogas per tonne OWF.

The Krüger company developed the **Bigadan Process** in Denmark. The system is used to treat a mixture of livestock manure, organic industrial waste and household waste. This way of digesting is called co-digestion. More than 20 plants are in operation in Denmark. In Kristianstad in Sweden, the same process is used, operating since 1996. The digester is fed with manure, organic household waste and industrial waste. The industrial waste includes gastrointestinal waste from abattoirs and bio-sludge from a distillery, as well as potato and carrot waste. The solid waste is automatically fed into a coarse shredder and cut into pieces of approximately 80 mm. After a magnetic separator has removed metals, a fine shredder cuts the waste into 10 mm pieces before being mixed with manure and bio-sludge. The mixture is transported to a primary mixing tank. After homogenisation, the biomass is pumped into two pasteurisation tanks at 70 °C. Via a heat exchanger the slurry enters a stirred digester, which operates at 38 °C with a hydraulic retention time of 20-24 days. The daily amount of biomass digested is approximately 200 tonnes producing 8,000-9,000 Nm^3 biogas/day. The total yearly input is approximately 70,000 tonnes corresponding to approximately 20,000 MWh/year. Approximately 10% of the biogas is used for operation of the plant.

4.3.1.2 Dry fermentation systems

High-solids anaerobic digestion systems have been developed to digest solid wastes (particularly municipal solid waste or MSW) at solids contents of 30% or above. High-solids systems enable the reactor size to be reduced, require less process water and have lower heating costs. A number of commercial and pilot scale plants have been developed including:

- the Valorga process [15], [19], [20];
- the Dranco process [15], [20], [21];
- the Kompogas process [15], [20];
- the Biocel process [15], [22], [23].

The **Valorga system**, a semi-continuous one-step process, was developed in France. The installation at Amiens combines four mesophilic high-solids reactors with the incineration of residues and non-digested matter. Mixing within the reactor is carried out by reverse circulation under pressure of a small proportion of biogas. In the installation in Tilburg, before entering the anaerobic step, the separately collected VFY waste is screened and then crushed to decrease particle size to below 80 mm. After crushing, the waste is intensively mixed with part of the excess process water and heated by steam injection. The biogas produced has a methane content of 55-60%. The biogas can be purified to a methane content of 97% which is then fed into the gas network (Tilburg plant), used to produce steam for an industrial process (Amiens) or for heating and electricity production (Engelskirchen). The specific methane yield is between 220 - 250 m^3/tonne of total volatile solids (TVS) fed to the digester or between 80 - 160 m^3/tonne of waste fed, depending on waste characteristics. The process operates at solids contents typically ca. 30% with residence times between 18-25 days. The waste is diluted in order to keep the TS content of the mixture at approximately 30%.

The **Dranco (Dry Anaerobic Composting) system** was developed in Gent, Belgium. The system operates at high solids content and thermophilic temperatures. Feed is introduced daily at the top of the reactor, and digested material is removed from the base at the same time. Part of the digested material is recycled and serves as inoculation material, while the remainder is de-watered to produce organic compost material. There is no mixing within the reactor, other than that brought about by downward plug-flow movement of the waste. The total solids content of the digester depends on the waste material source but is in the range 15 - 40%. Reactor retention time is between 15 - 30 days, the operating temperature is in the range 50 - 58 °C and the biogas yield is between 100 - 200 m^3 / tonne of waste feedstock.

The **Kompogas system** is a high-solids thermophilic digestion system developed in Switzerland. The reaction vessel is a horizontal cylinder into which feed is introduced daily. Movement of material through the digester is in a horizontal plug-flow manner with digested material being removed from the far end of the reactor after approximately 20 days. An agitator within the reaction vessel mixes the material intermittently. The digested material is de-watered, with some of the press water being used as an inoculum source and the remainder being sent to an anaerobic wastewater treatment facility that also produces biogas.

The **Biocel process** is a high-solids batch process operated at mesophilic temperatures. Wastes are mixed with inoculum before being sealed into unstirred batch reactors. Wastes are kept within the digestion vessel until biogas production ceases. Leachate produced during the digestion process is heated and recirculated through the waste. A full-scale plant at Lelystad in The Netherlands commenced operation in September 1997. It processes 50,000 tonnes per year of Source Separated organic fraction of Municipal Solid Waste (SS-MSW) yielding energy and compost. The retention time is approximately 21 days [23].

4.3.1.3 Two-phase digestion systems

The idea of two- and multi-stage systems is that the overall conversion process of the waste stream to biogas is mediated by a sequence of biochemical reactions which do not necessarily share the same optimal environmental conditions [20]. The principle involves separation of digestion, hydrolysis and acidogenesis from the acetogenesis and methanogenesis phases. Optimising these reactions separately in different stages or reactors leads to a larger overall reaction rate and biogas yield [24]. Concentrated slurries and waste with a high lipid concentration should preferably be treated in a one-stage digester for two reasons. (1) Lipids will not be hydrolysed in the absence of methanogenic activity. (2) The possible decrease of the lipid-water interface in the first stage of a two-stage sludge digester can result in a longer SRT in the second stage [25]. Moreover hydrolysis and acidification of proteins and carbohydrates are not promoted by acidogenic conditions [4].

There are two kinds of two-phase digestion systems, one in which the different stages are separated, based on a wet fermentation, and one based on dry fermentation, in which only the percolate experiences a second methanogenic stage. The first system operates on dilute materials, with a total solids content of less than 10%. Unlike conventional low-solids digestion systems, which operate within a single reaction vessel, multiphase liquid systems separate the digestion process into two or more stages, each taking place in a separate reaction vessel. Systems include:

- The BTA-process [15];
- The BRV process [15], [20].

The **BTA-process** was developed in Germany as a three-phase liquid system for digestion of the organic fraction of MSW [15]. The waste is mixed with recycled process water before entering an acidification reactor. In this vessel, soluble organic material such as sugars and starch are rapidly converted into organic acids. The waste is then dewatered, and the liquid portion fed into a fixed-film methane reactor. The solids, containing polysaccharides such as cellulose are then mixed with more process water and fed into a hydrolysis reactor, where hydrolysis and acidification of the more resistant fibres takes place. After hydrolysis, waste is once more de-watered, the liquid effluent is fed into the methane reactor, and the solid fraction is removed and used as compost. Effluent from the methane reactor is used as process water to slurry incoming wastes.

The **BRV system** was developed in Switzerland and is an aerobic/anaerobic conversion system. The anaerobic phase is the Kompogas system, described earlier [15].

There is also a system, which consists of a dry fermentation stage followed by a liquid methanogenic stage. A number of different systems have been developed that use this configuration and they have been described as 'leach-bed' or percolation systems. Again a number of systems have been described but most apply the same principle. An example is the **Biothane-AN system** [15], in which solid wastes are placed batch-wise (at a high-solids concentration) into a reaction vessel. Process water is percolated through the waste, hydrolysis takes place and the resultant percolate is fed into a methane reactor. Effluent from the methane reactor is then recirculated through the hydrolysis vessel to generate further percolate. Normally, a series of batch hydrolysis vessels will feed a single methane reactor, to ensure a constant supply of percolate to the methane reactor.

4.3.2 Systems for wastewater treatment

High Rate Anaerobic Treatment systems (Figure 6, 7, 8), like the UASB (Upflow Anaerobic Sludge Bed) reactor, Anaerobic Filter and the Contact Process, are unfit for the digestion of concentrated slurries but suitable for diluted and concentrated wastewater and can be part of a multi-stage system. The sludge retention time is longer than the hydraulic retention time, as the sludge is retained in the reactor by using internal settler systems or external settlers with sludge recycling or fixation of biomass on support material. In single-phase high rate systems, all anaerobic stages take place at the same time.

High rate systems are most suitable for waste streams with a low suspended solids content. Different types, used world-wide for the treatment of wastewater are [1], [26]:

- Contact process; Biobulk-system by Biothane [27];
- Upflow Anaerobic Sludge Bed (UASB);
- Anaerobic Fixed Film Reactor (AFFR);
- Fixed film Fluidised Bed system;
- Expanded Granular Sludge Bed (EGSB);
- Hybrid systems;
- Anaerobic Filter (AF).

Biobulk is a conventional anaerobic contact process, with sludge recirculation, applicable for

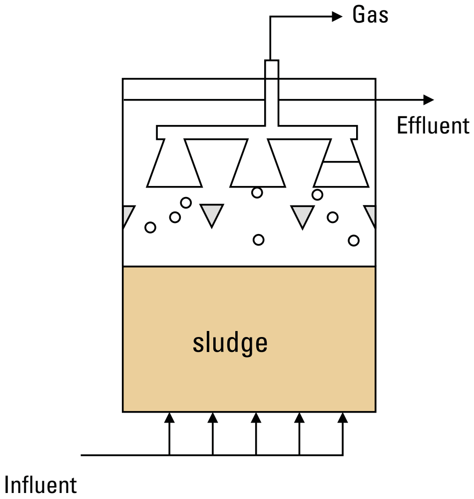


Figure 6. Schematic diagram of a UASB.

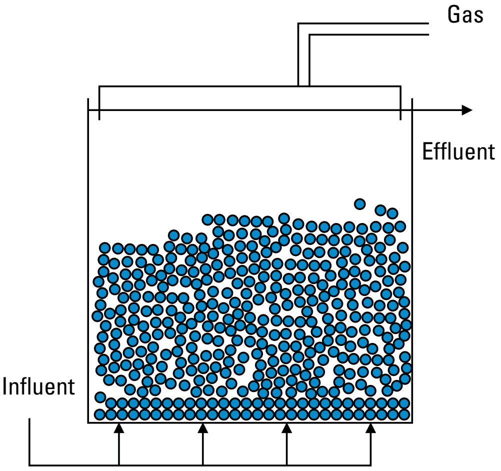


Figure 7. Schematic diagram of an Anaerobic Filter (AF).

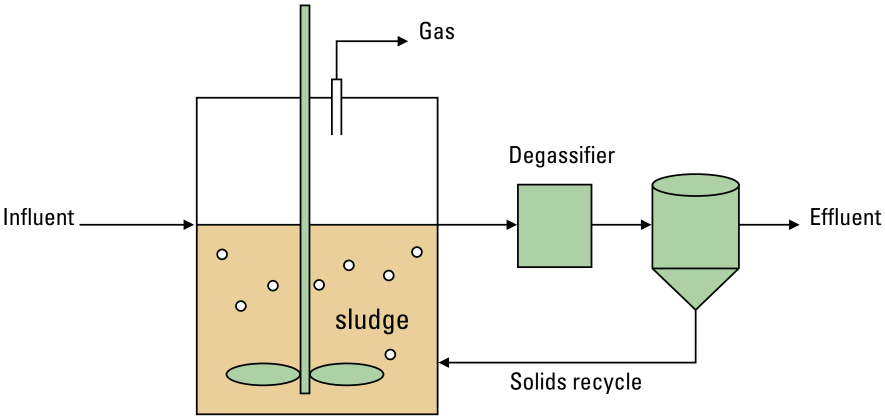


Figure 8. Schematic diagram of an Anaerobic Contact (AC) process.

Figure 9. UASB reactor at Cerestar, Sas van Gent, The Netherlands. Photo by courtesy of Biothane Systems International.

waste streams containing high strength COD / BOD concentrations and fats, oils and grease concentrations higher than 150 mg/l. Biobulk is a 'medium loaded' system with volumetric loading of 2-5 kg/COD/m^3/day.

The Biobulk Continuously Stirred Tank Reactor (CSTR) has specially-designed mixing capability to ensure the wastewater is in constant contact with the biomass.

The process is applied in ice cream plants and other food processing facilities which discharge effluents high in biodegradable fats and oils. Removal efficiencies with this technology have been found to consistently average above 90% with respect to COD and BOD and close to 75% with respect to the organic fraction of TSS.

The **Upflow Anaerobic Sludge Bed (UASB)** concept was developed in the late 1960's at Wageningen University in The Netherlands. The Dutch beet sugar firm, CSM, developed the basic technology for wastewater treatment in several sugar factories. Companies such as Paques and Biothane carried out further development of the system on a commercial basis (Figure 9).

The key to the commercialisation step was the design and engineering of simple but efficient internal topworks (settler) to effectively degasify the biomass and ensure its retention in the reactor vessel. Wastewater enters the bottom of the reactor vessel through an inlet distribution system and passes upward through a dense anaerobic sludge bed. Soluble COD is then converted to biogas, which is rich in methane and an upward circulation of water, establishing well-settleable sludge. The specially constructed settler sections allow an effective degasification so sludge particles devoid of attached gas bubbles, sink to the bottom establishing a return downward circulation (see also Figure 6).

Upward flow of gas-containing sludge through the blanket combined with return downward flow of degassed sludge creates continuous convection. This ensures effective contact of sludge and wastewater without the need for any energy consuming

mechanical or hydraulic agitation within the reactor. The unique design of the reactor allows a highly active biomass concentration in relation to soluble organic solids passing through the sludge bed and is responsible for the very high loading rate (short hydraulic retention time), which can be readily achieved. When the UASB is applied for wastewater containing suspended solids (like sewage), flocculent sludge will grow rather than granular sludge [1]. Flocculent sludge can also result in sufficient sludge retention for removal of organic material.
A successful version of this concept is the **Internal Circulation (IC) reactor,** characterised by biogas separation in two stages in a reactor with a high height/diameter ratio and gas-driven internal effluent circulation (Figure 10). The IC system can process high upflow liquid and gas velocities, which enables treatment of low strength effluents at short hydraulic retention times, and treatment of high strength effluents at high volumetric loading rate. In recent years IC technology has been successfully applied at full scale on a variety of industrial wastewater types [28].

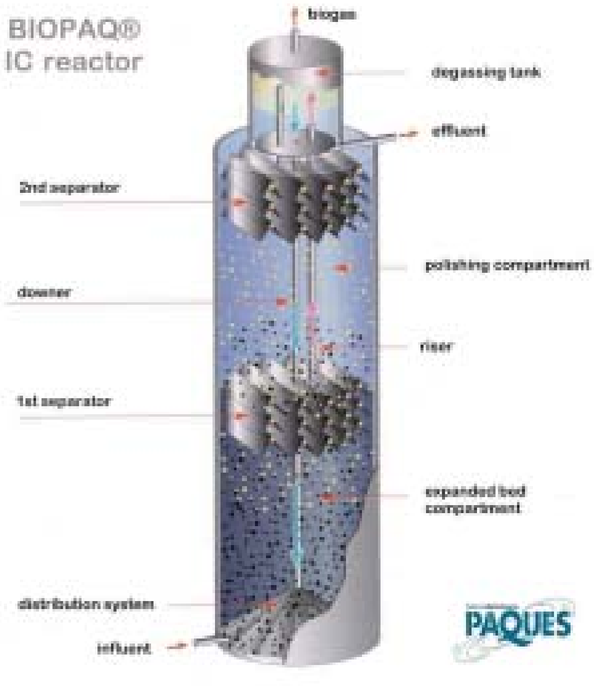


Figure 10. Schematic diagram of Internal Circulation (IC) reactor. Courtesy of Paques Biosystems B.V.

The **Expanded Granular Sludge Bed (EGSB)** process incorporates the sludge granulation concept of UASB's. The main improvement of the EGSB system, trademarked 'Biobed' (by the company Biothane), compared to other types of anaerobic fluidised or expanded bed technologies is the elimination of carrier material as a mechanism for biomass retention within the reactor. This process is therefore perceived either as an ultra high rate UASB or a modified conventional fluidised bed. Applications for Biobed include wastewater from breweries, chemical plants, fermentation industries and pharmaceutical industries. This system is designed to operate at high COD loading; it is very space efficient, requiring a smaller footprint size than a UASB system.

Anaerobic Fixed Film Reactors (AFFR) contain a mixed population of bacteria immobilised on the surfaces of support medium, and have been successfully applied in the treatment of high-strength effluent treatment [29].

The **hybrid system** was developed to overcome the problems in UASB and AF systems. In an AF reactor, the presence of dead zones and channelling in the lower part of the filter generally occurs. In UASB systems sludge washout may be a problem when the wastewater contains large fractions of suspended solids. The hybrid system combines both the fixed bed system (at the top of the reactor) with the UASB system. The filter zone in the hybrid reactor has as well a physical role for biomass retention as biological activity contributing to COD reduction [30].

4.4 Waste streams

The various types of waste streams which can be digested for the recovery of energy in the form of methane, can be divided as follows:

1. Solid wastes:
- domestic wastes, such as separately collected Vegetable, Fruit and Yard waste (VFY);
- organic residual fraction after mechanical separation of integral collected household waste (grey waste);
- agricultural wastes (crop residues);
- manure.

Figure 11. Vagron plant (Groningen) for separation and digestion of the organic fraction of MSW. Photo by courtesy of Vagron BV.

2. Waste slurries:
- liquid manure;
- sewage sludge;
- urine and faeces;
- industrial waste (e.g. fat-, slaughterhouse and fish wastes).

3. Wastewater:
- industrial wastewater (especially from the food and beverage industry);
- domestic wastewater (sewage).

4.4.1 Vegetable, Fruit and Yard waste and organic residual of Municipal Solid Waste

Vegetable, Fruit and Yard (VFY) waste is the organic fraction of domestic solid waste and contains the following components [31]:

- leaves, peels and remains of vegetables, fruits, potatoes;
- all food remains;
- egg-shells, cheese-rinds;
- shells of nuts;
- coffee-filters, tea-leaves and tea-bags;
- cut flowers, indoor plants (without clod), grass, straw and leaves;
- small lop waste and plant material from gardens (no soil);
- manure of pets, pigeons, rabbits (no cat's box grit).

In The Netherlands, VFY waste is mainly composted, but there are two installations in which VFY waste is digested, one in Tilburg (Valorga) and one in Lelystad (Biocel). Grey waste is treated in Groningen (Vagron; Figure 11).

A second plant has been constructed in Heerenveen and is now in the start-up phase. A comparison of the three plants based on measurements from practice is given in Figure 12. The methane content in the biogas is 55-70% [15]. The highest amount of biogas per tonne biowaste is produced in the Vagron plant, operated at thermophilic conditions. The other plants are operated under mesophilic conditions. Moreover the organic waste fraction is collected in a different manner. The organic fraction treated in the Valorga plant contains a low amount of yard waste. Valorga and Biocel are both dry fermentation processes, the main differences being that the Valorga system employs mixing using reverse circulation of the biogas, while in the Biocel process only leachate circulation is employed. Moreover Biocel is a batch system while Valorga is a continuous system. The retention time in the Biocel is approximately 21 days, in the Vagron and Valorga plant approximately 18 days. A more detailed scheme of the Vagron plant is given in Appendix III.

4.4.2 Agricultural wastes

Agricultural wastes contain remains of the process such as cut flowers, bulbs, verge grass, potatoes, chicory, ensilaged weed etc. This type of waste is suitable for re-use after fermentation, as the type of waste collected is 'cleaner' than ordinary VFY [34].

4.4.3 Manure and liquid manure

In The Netherlands approx. 35 on-farm manure digestion installations were in operation in the period 1978 to 1993. In 1993, only four installations still remain operational [31]. In 1995, the only central digester, a medium scale demonstra-

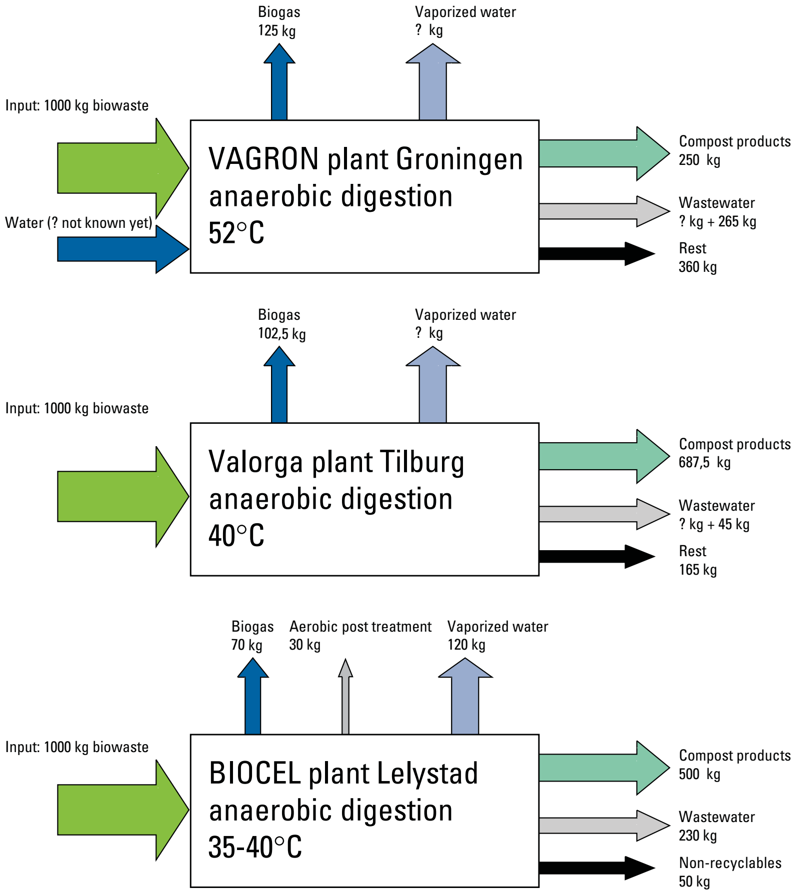


Figure 12. Mass-balances for the three operating digestion plants on the organic fraction of Municipal Solid Waste. Data Vagron from [33], data Valorga from [32], Biocel scheme adapted from [23].

Figure 13. Biogas plant for manure digestion Praktijkcentrum Sterksel, The Netherlands. Photo by courtesy of www.energieprojecten.com.

TABLE 1. *Typical composition of the influent pig and dairy cattle manure in The Netherlands and in Switzerland (All values are given in kg/m^3) [7].*

	The Netherlands Dairy Cattle	**Switzerland Dairy Cattle**	**Switzerland Pig**
Total Solids	85.4	83	43
Volatile Solids	74.7	73	74
NH_4^+-N	2.2	1.5	1.9
Total COD	101	-	-
Dissolved COD	27.6	-	-
VFA (COD)	11.1	2.6	7.4
pH	7.5	7.4	7.2

tion plant at Daersum was closed down. The full-scale plant, named PROMEST in Helmond where 600,000 tonnes animal manure was processed per year was also closed in the same period. The PROMEST processing plant consisted of anaerobic digestion followed by separation of liquid /solids and treatment of the liquid, in order to produce clean water and granulated fertilisers. Until recently manure digestion was not taken in operation in The Netherlands. Farm scale digesters became too expensive and labour intensive and farmers were not willing to pay for manure processing in the central digesters. In summary the reasons are [35]:

- Low return for biogas and electricity (low prices);
- Strict regulation for the application of co-digestion. Co-digestion can increase the gas yield per m^3 reactor content per day, but legislation prevented the application of digested co-substrates on agricultural fields [36];
- Insufficient collaboration effort between the agricultural sector, energy sector and the waste sector to introduce this technique.

The situation has improved since 1997 due to the following development [35]:

- Increased price for disposal of organic waste due to the ban on organic matter landfill;
- Higher prices for renewable energy;
- The need for selective manure distribution due to stronger manure legislation;
- Lower capital/investments costs due to lower interest rates and fiscal incentives;

Digestion of manure is economically efficient when mixed with other organic waste streams, like VFY waste, left-over feed, roadside grass, old frying fat etc. This technique is called co-digestion and widely used in Denmark. In Denmark a specific biogas production of ca. 37 m^3 per tonne of biomass is achieved using co-digestion, while only using manure approximately 20 m^3 per tonne biomass is produced. At the Research Institute for Animal Husbandry in Lelystad (The Netherlands) a study has been conducted on the feasibility of anaerobic manure digestion for individual Dutch dairy and pig farms. The most important conclusion of the report is that manure digestion can be economically viable given a sufficiently large farm and economic feasibility is dependent on the market value of electricity. The reduction of CO_2 emission is also emphasised. Given these trends, manure digestion will become an increasingly interesting option in the coming years. At present several demonstration plants are operational in The Netherlands, which apply co-digestion, limited to plant materials, for example at a dairy farm in Nij Bosma Zathe, in Leeuwarden and at a pig farm in Sterksel, Brabant (see Figure 13). The volume of the digester is dependent on the concentration of the manure. A higher concentration ensures less volume is needed to apply the same hydraulic retention time and biogas production. The concentration of manure is dependent on the method used to clean out stables. A typical composition of pig and dairy cattle manure in The Netherlands and Switzerland is shown in Table 1. Concentrations have been increased as a result of reduction in 'spilling' water. The biodegradability can also vary with the kind of manure. The biodegradability of dairy manure is much lower due to the very efficient digestive track of ruminants. In digestion of pig-slurry about 40% of the COD will be converted to methane-COD [37], while in the digestion of cow slurry this is approximately 25% [7]. The methane content of the biogas varies between 55-70% [38]. An overview of initiatives in The Netherlands for manure digestion is given as Appendix IV.

4.4.4 Sewage sludge

Sewage sludge contains primary sludge as a result of a pre-settling stage of sewage and secondary sludge as a result of sludge growth during aerobic wastewater treatment. To stabilise sludge before further treatment, anaerobic digestion is commonly used. In The Netherlands in 2001 approximately 100 one-step digesters were in operation [39]. The average process conditions are summarised in Table 2. From a theoretical point of view approximately 50 large sewage treatment plants (capacity higher than 50,000 p.e.) in The Netherlands could improve efficiency if anaerobic digestion was applied [39]. Typical values for the amount of total solids in the influent are 4% to 6% [40]. Due to a high number of one-step digestion installations in the Netherlands not performing at optimum conditions with respect to biogas production, Royal Haskoning B.V. performed research to optimise these conditions [40]. One of the conclusions was that process factors such as retention time, loading rate and mixing have a larger influence on the degradation of organic material than temperature. Optimisation of these factors can lead to an increase in biogas production of approximately 25%.

The dry matter of sludge contains approximately 70% organic matter. During digestion this can be reduced to approximately 45%. As a result of this reduction and the increased de-waterability

TABLE 2. *Typical process parameters of sludge digestion installation in The Netherlands, minimum, maximum and average value [40].*

Parameter	Minimum value	Maximum value	Average
Digester Volume (m^3)	450	26,464	3,963
Temperature (°C)	30	35	33
HRT (days)	11	77	31
Influent Dry matter (kg/day)	512	55,000	6,641
Influent Organic matter (kg/day)	255	41,250	4,581
Loading (kg dry matter/m^3/day)	0.53	4.66	1.52
Removed (kg dry matter/m^3/day)	0.10	1.40	0.54
Gas production (m^3 CH_4/day)	74	13,000	1,216
Gas production (m^3 CH_4/kg dry matter input)	0.116	2.063	0.682

the final sludge volume after de-watering is decreased. The digestion of aerobic biomass (secondary sludge) is limited due to slow dying and lysis of aerobic microbial cells. In The Netherlands the further treatment, after digestion, is mainly dewatering and incineration of the solid fraction. The latter represents the largest cost in the treatment of domestic sewage. Digested sewage sludge cannot be used in agriculture as a result of heavy metals pollution.

4.4.5 Industrial waste slurry and wastewater

Industrial wastewater is heterogeneous, both in composition and volume. Effluents from the Food & Beverage (F&B) industry contain the highest concentration of organic compounds [41]. Anaerobic wastewater treatment is widely applied in this branch of industry as in the Pulp and Paper industry, as is shown in Table 3 and Figure 14.

TABLE 3. *World-wide application of high rate anaerobic systems adapted from a vendor's database [26].*

Application	Number of plants
Breweries and beverages	304
Distilleries and fermentation	206
Chemical	61
Pulp and paper	130
Food	371
Landfill leachate	20
Undefined/unknown	70
Total in database	**1,162**

Food and Beverage industry

The most important Food and Beverage industries can be summarised [41]:

- Slaughterhouses and meat-processing
- Dairy
- Fish-processing
- Starch-processing
- Sugar
- Edible oil
- Beverages and distilleries
- Fruit and vegetable processing
- Coffee processing

As each process involves different compounds and the majority of these industries do not operate continuously over a 24 hour period each waste-water characteristic shown below will vary with time:

1. Volume (varying from 0.1-175 m^3/tonne product);
2. BOD/COD concentration and ratio (BOD 30-40 g/l; COD 70-80 g/l);
3. pH (in the range 3-12);
4. Temperature (10-100 °C);
5. Concentration of nutrients, chemicals, detergents.

If the wastewater does not contain a large percentage of suspended solids, a high rate system is usually applied. Otherwise removal of solids in a primary treatment system can be applied. These solids can be treated, e.g. to produce animal feed or fertiliser, or can be digested separately or, in the worst case, incinerated. When solids are not removed in advance, the HRT should be increased so a sufficient SRT is provided [5].

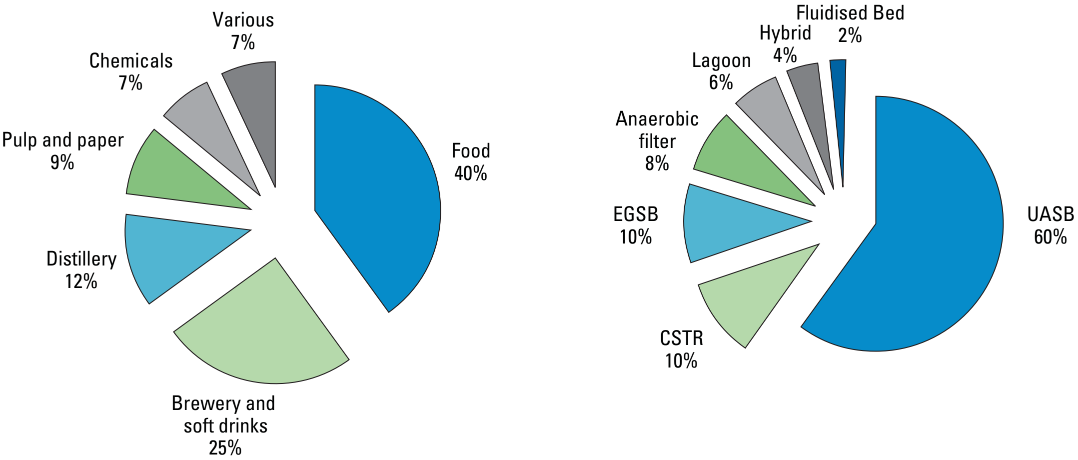


Figure 14. Industries using Anaerobic Digestion for wastewater pre-treatment and types of AD systems used for industrial wastewater pre-treatment plants [42].

An overview of the characterisation and anaerobic biodegradability of different industrial wastewater streams is given as Appendix II.

4.4.6 Domestic wastewater

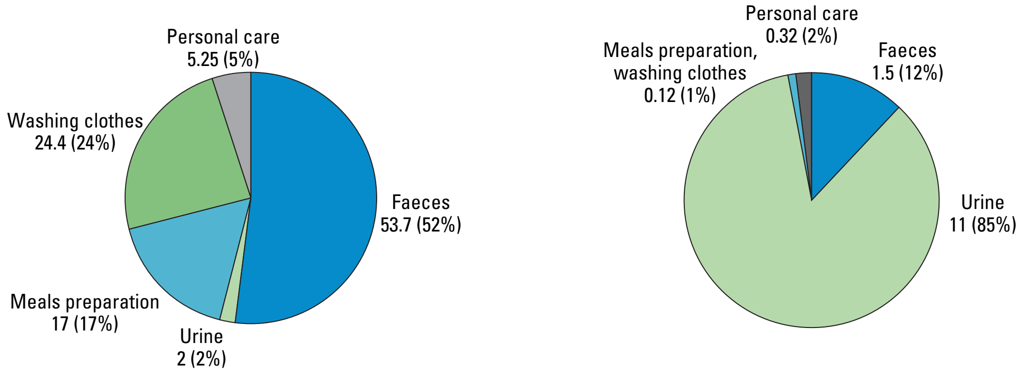
Domestic wastewater is composed of different flows, which can be discharged separately or combined:

1. **Black water:** Wastewater from flushing the toilet contains faeces, urine and cleansing materials. Black water contains a high number of pathogens. The concentration of this waste stream is dependent on the amount of flushing water used. In 'conventional' European and northern American toilets about 10 litres per flush is used. Poor-flush toilets use 2-5 litres per flush and modern vacuum toilets only use ca. 1 litre per flush.
2. **Grey water:** Wastewater from in-house usage such as bathing, washing and cleansing does not contain excreta and therefore less pathogens and little nutrients (N, P, K). Volumes and concentration are strongly dependent on water consumption patterns and waste handling.
3. **Combined wastewater:** Both black and grey water combined with urban run-off water, such as rain and drain water.

Combined wastewater is too diluted in western countries to be treated anaerobically; it would take more energy to heat the wastewater than the amount of methane formed. Treatment at low temperatures is possible but long HRT's are necessary, in order to provide sufficient SRT for hydrolysis and methanogenesis. Recently, new technologies for treatment of raw domestic sewage at low

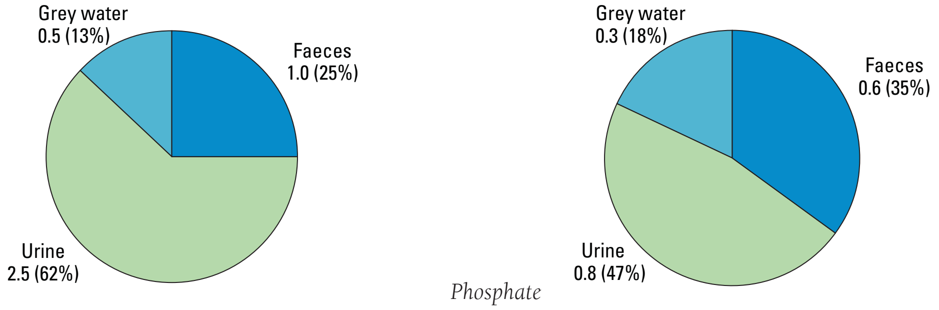
TABLE 4. *Composition of raw sewage in various cities in the world. The sewage is mainly of domestic origin [44]*

Characteristic	**Pedregal, Brazil**	**Cali, Colombia**	**Bennekom, The Netherlands**	**Accra, Ghana**
Total Suspended Solids (TSS mg/l)	429	215	160	980
Volatile Suspended Solids (VSS mg/l)	252	107	70	769
BOD (mg/l)	368	95	230	879
COD (mg/l)	727	267	525	1546
Total Nitrogen (mg N/l)	44	24	75	93
Total Phosphorus	11	1.3	18	16
Alkalinity	388	120	350	491



COD *Nitrogen*

Figure 15. Organic matter (g COD) and Nitrogen (g) produced in domestic wastewater per person per day [45].



Potassium *Phosphate*

Figure 16. Potassium (g) and phosphate (g) produced in domestic sewage per person per day [45].

temperatures have been developed and tested on pilot scale [30], [43]. In developing countries anaerobic treatment of domestic sewage is an appropriate technology as temperatures are favourable. Several full-scale UASB systems are applied in South America, India, and recently Ghana (West Africa). The composition of sewage is given in Table 4. The maximum anaerobic biodegradability of domestic sewage is 74% [30]

Wastewater quality and quantity

A large fraction of domestic wastewater components, viz. organics, nitrogen, phosphorus, potassium and pathogens are produced in small volumes, viz. as faeces plus urine. The latter is shown in Figures 15 and 16. The diagrams show that 85% nitrogen, 2% organic matter, 46% phosphorus and 62% potassium present in domestic wastewater originates from the urine, while 11.5% nitrogen, 52% organic matter, 35% phosphorus and 25% potassium originates from faeces. The mean production of faeces plus urine amounts to 1.5 l per person per day. This volume contains 96.5% nitrogen, 54% organic matter, 81% phosphorus (when no phosphorus is used in washing powders) and 97% potassium produced per person per day. Moreover, faeces contain the largest amount of pathogens. All these compounds are diluted with clean water when flushing toilets and moreover when shower and bath water, washing water and kitchen water are added, before entering the sewer. In the sewer rainwater is also added. Finally a large volume of water is transported to the wastewater treatment system, where the different compounds should be removed, consuming a large amount of energy when conventional aerobic treatment is applied. The former clearly shows that separation of toilet wastewater (black water) can prevent the pollution of other wastewater streams (grey water) with organics, nutrients and other salts and pathogens.

The section Environmental Technology of Wageningen University researches the separate collection, transport and treatment of black and grey water. The concept will be demonstrated in 2005. In Germany the concept is already applied in practice at a few locations, for example in a new housing estate in Lübeck.

4.5 Utilisation of biogas as a renewable energy source

4.5.1 Introduction

Biogas or landfill gas is primarily composed of methane (55-75 vol%), and carbon dioxide (25-45 vol%) with smaller amounts of H_2S (0-1.5 vol%) and NH_3 (0-0.05 vol%). The gas mixture is saturated with water vapour and may contain dust particles and trace amounts of H_2, N_2, CO and halogenated compounds depending on the feedstock and process conditions [46]. The fuel value of biogas containing 55-75 vol % methane ranges between 22–30 MJ/Nm^3 (Higher Heating Value) and 19-26 MJ/Nm^3 (Lower Heating Value) respectively.

Biogas can be utilised for the production of heat, co-generation of electricity and heat (CHP) or for upgrading to natural gas or fuel gas quality. A part of the biogas energy is utilised on site to provide for the internal energy requirement of the plant (digester heating, pumps, mixers etc.).

The amount of energy used for plant operation ranges between 20 and 50% of the total biogas energy contents depending on climate and technical specifications. For systems treating solid biowastes internal energy use is around 20%. In [47] a biogas plant in Germany is described treating 26,000 tonnes of fruit and vegetable wastes and 4,000 tonnes of park wastes per year. The plant produces 2.8 Million Nm^3 of biogas per year (60 vol% methane) with a total energy content of 16,650 MWh. The biogas is converted in a CHP system into electricity (35%) and heat (50%) with 15% energy loss. The energy balance indicates that the plant consumes 23% of the energy content of the total biogas production. The electricity surplus for export to the grid amounts to 3,510 MWh/year or 21% of the biogas energy content [47].

In the remaining part of this section techniques for utilisation and upgrading of biogas and landfill gas are described, including the required purification processes. For reviews the reader is referred to [46], [48], [49].

4.5.2 Generation of heat and combined heat and power generation (CHP)

Heat production in gas heater systems

Heat production in gas heater/boiler systems does not require a high gas quality [46]. Reduction of the H_2S content to below 1,000 ppm is recommended to prevent corrosion. Furthermore it is advisable to condense the water vapour in the gas to prevent interference with the gas nozzles. Removal of water will also remove a substantial amount of the H_2S [46].

Gas engine and gas turbine CHP systems

The utilisation of biogas in internal combustion engines ('gas engines') is a long established technology. Engine sizes range from 45 kWe in small plants to several MWe in large biogas plants or landfill sites. Mostly used in large-scale applications are diesel engines rebuilt to spark ignited gas engines or dual fuel engines with 8-10% diesel injection [46]. Small-scale CHP systems (< 45 kWe) reach an electrical efficiency of 29% (spark ignition) and 31% (dual fuel engine). Larger engines can reach an electrical efficiency of 38% [46]. Up to 50% of the biogas energy content is converted to heat which can partly be recovered from the exhaust gas (high temperature heat) and the cooling water and oil cooling (lower temperature heat) [48], [49]. Energy losses are about 15%. Utilisation of biogas in gas engines may require removal of H_2S, NH_3 and particles depending on manufacturers' specifications (see Table 5).

Gas engine CHP systems have a higher electrical efficiency than gas turbine CHP systems and lower specific investment costs. Maintenance costs for gas engines are higher than for turbines. The use of gas turbines in CHP systems may be more economical in applications with a large, constant high value heat requirement (> 110 °C) or in large installations of several MWe's capacity [49]. A restriction of gas turbines is the limited flexibility with varying gas flows because a reduced gas inflow leads to a decreased efficiency [48].

Fuel cell CHP systems

Fuel cells make use of direct electrochemical conversion of the fuel with oxygen to generate electricity and heat with near-zero emissions. The fuel (methane in the case of biogas) is converted to hydrogen by the action of a catalyst or high temperature steam reforming. The H_2 is then electrochemically converted to electricity and heat. Water and CO_2 are the main by-products. The potential electrical efficiency is > 50% while the thermal efficiency is approx. 35%. For utilisation of biogas two fuel cell types are most relevant for the near future. Phosphoric acid fuel cells (PAFC) are at present applied in a number of 200 kW to 2 MW power plants operating on natural gas with a practical electrical efficiency of 41% [46]. The PAFC operates at approx. 200 °C which allows usable heat recovery. Utilisation of biogas in a PAFC requires near-complete removal of sulphides and halogenated compounds [46], [50]. In Japan a 200 kWe PAFC is used in a brewery for conversion of biogas from wastewater effluent [51]. Before entering the fuel cell the biogas is purified in a pre-treatment section composed of a desulphuriser, an ammonia/salt removing unit, a buffer tank and a gas analyser. Impurities are adequately removed while at the same time CO_2 is removed from the gas. The overall conversion efficiency (electricity + heat) is 80% [51]. Solid Oxide Fuel Cells (SOFC) operate at temperatures > 900 °C. The SOFC has a relatively high tolerance for impurities, although it also requires near-complete removal of sulphides and halogens. The high operating temperature allows direct methane conversion and recovery of high temperature heat. The attainable electrical efficiency on natural gas is > 40%. In The Netherlands the utilisation of biogas from animal manure in an SOFC system is currently being explored at farm scale [52].

The utilisation of biogas in fuel cells is an important strategy to enhance the efficiency of electricity generation. A substantial cost reduction of fuel cells is however required for large-scale application. The conversion of fermentation gases in fuel cells is being explored in ‘BFCNet’: ‘Network on Biomass Fermentation Towards Usage in Fuel Cells’ [53]. The objectives of BFCNet include R&D and demonstration, and the development of standards on EU level.

4.5.3 Upgrading of biogas and landfill gas to natural gas and vehicle fuel quality

Upgrading of biogas and landfill gas to natural gas standards and delivery to the (local) natural gas network is a common practice. In The Netherlands 45% of the produced landfill gas was upgraded to natural gas quality in 1995 [48]. Landfill gas is the final product from biodegradation of organic materials present in landfill sites and consists mainly of methane (50-60 vol%) and carbon dioxide (40-45 vol%). It further contains sulphur (0-200 mg/m^3) and chlorinated and fluorinated hydrocarbons. The Higher Heating Value is 20-24 MJ/m^3 [48]. To reach natural gas quality the landfill gas undergoes extensive dewatering, removal of sulphur components in a bed charged with impregnated active carbon or iron oxide, and removal of halogens by absorption in an active carbon bed. Further upgrading involves changing the composition of the gas by separating the main components methane and carbon dioxide in a high calorific (methane rich) and a low calorific (methane poor) gas flow in order to attain a calorific value and 'Wobbe index' similar to natural gas. Upgrading technologies include chemical absorption, Pressure Swing Adsorption and membrane separation. Before delivery to the grid the gas must be free from solid and fluid components and it must be pressurised [48]. Upgrading of biogas from controlled digestion makes use of similar technology.

Upgrading of biogas to transport fuel quality is common practice in several European countries (including Sweden, the Czech Republic, France), the USA and New Zealand. World wide 23 facilities for production and upgrading of biogas to transport fuel standards were in operation in 1999 [46]. Sweden produces an amount of biogas of 1,35 TWh/year primarily in sewage treatment plants and also in landfill sites and industrial wastewater treatment plants. Approximately 100 GWh/year (10 Million m^3) are currently used as vehicle fuel. Based on experiences gained from projects with municipal fleets of busses and taxis, the Swedish program now aims for commercial expansion of vehicle fleets and infrastructure for (upgraded) biogas refuelling stations [54]. Upgraded biogas can be used in existing engines and vehicles suitable for natural gas. At present approx. 1.5 million natural gas fuelled vehicles are in use world wide. Sulphur, water and particles must be removed to prevent corrosion and mechanical engine damage. Carbon dioxide must be removed to reach a required methane content

TABLE 5. *Indicative gas quality requirements for various applications. Sources: [46], [48], [49].*

Component:	**H_2S**	**CO_2**	**Halogens (Cl, F; landfill gas)**	**Dust particles**	**H_2O**
Utilisation:					
Gas heater/boiler	< 1000 ppm 1)				Removal advisable
Gas engine		Minimum LHV 3) 13-21 MJ/m^3	Cl and F3) 60-80 mg/m^3		Humidity 3) < 70-80%
- per 10 kWh (LHV) input3)	< 1150 – 2000 mg			< 50 mg/m^3	
- per m^3 of biogas3)	< 700-1200 mg/m^3			< 30 mg/m^3	
Fuel cells					
- Phosphoric Acid Fuel Cell	< 10 ppm4		Near-complete removal required	Removal required	
- Solid Oxide Fuel Cel	< 10 ppm4)				
Vehicle fuel 5)	Max. 23 mg/Nm^3	Max. 3 vol%	Removal required		Max. 32 mg/Nm^3
Natural gas quality6)	Sulphur < 5mg/m^3 7)		Cl < 5mg/ m^3	Removal required	Dew point at –10°C

1) removal required if input limits are exceeded
2) data provided by Jenbacher (2002) per 10 kWh (LHV) gas input for gas engines ranging between 300-3000 kW; data were calculated per m^3 biogas assuming 60 vol% methane. The maximum allowable NH_3 concentration is 55 mg/10 kWh [49]. If an NO_x (and CO) catalyst is used to purify the engines' exhaust gases, near-complete removal of halogens from the biogas is required.
3) according to ref. [48].
4) preferably lower i.e. < 1 ppm.
5) specifications for transport fuel used in Sweden. From ref. [46].
6) natural gas composition in The Netherlands. From ref. [48].
7) removal (to about 5 vol%) required to attain suitable combustion value and Wobbe index.

of 96 - 97 vol%. The gas is compressed and stored at a pressure of 250 bar for distribution, using the same technology as for compressed natural gas [46].

Demands for the removal of components differ depending on the biogas application. Indicative quality requirements for several applications are summarised in Table 5.

4.5.4 Purification technologies

Raw biogas should be treated to prevent corrosion of installed equipment or to achieve adequate quality standards for use as a natural gas substitute or transport fuel. An overview of available techniques for biogas treatment is provided in Table 6.

4.6 The economics of anaerobic digestion

4.6.1 Introduction

In assessing the economic viability of biogas programs, it is useful to distinguish between three main areas of application:

1) Anaerobic treatment of household waste(water)
    a) DeSaR (Decentralised Sanitation and Reuse); including community-on-site anaerobic treatment of domestic waste(water) and organic household waste
    b) central digestion of the organic fraction of household waste
        i) source separated at the household

TABLE 6. *Overview of techniques used for biogas treatment [55].*

Compound removed	Technique	Principle
Water/Dust	Demister	Physical
	Cyclone separator	"
	Moisture trap	"
	Water trap	"
	Cooling in combination with demister	"
	Absorption to silica	"
	Glycol drying unit	"
H_2S	Air oxygen dosing$^{1)}$	Biological
	$FeCl_3$ dosing to digester slurry	Chemical
	Adsorption to Fe_2O_3 pellets	Physical-chemical
	Absorption with caustic solution	"
	Absorption with iron solution	"
	Absorption closed loop systems	"
	Membrane separation	Physical
	Biological filters	Biological
	Activated carbon filtration	Physical-chemical
	Molecular sieves	Physical
CO_2	Pressure swing adsorption	Physical-chemical
	Membrane separation	Physical
	Absorption techniques	Physical-chemical

1) The H_2S content can be reduced by adding a small amount of air at the end of the digestion process.

    ii) mechanically separated
  c) digestion of sewage sludge at a central sewage treatment plant
2) Anaerobic digestion of manure
  a) on-farm digestion for energy production
  b) central digestion for energy production
  c) central digestion and further processing (recovery/removal of nutrients from the liquid phase)
3) Anaerobic treatment of industrial wastewater and waste

In this section mainly 1b, central digestion of the organic fraction of household waste, and 2, anaerobic digestion of manure, are discussed. In each case, the economic feasibility of individual facilities depends largely on whether output in the form of gas (for cooking, lighting, heating and electricity generation) and solid and liquid by-products (for use as fertiliser/soil conditioner, fishpond or animal feed) can substitute for fuels, fertilisers or feeds, previously purchased. For example, a plant has a good chance of being economically viable when farmers or communities previously paid substantial percentages of their incomes for fuels (e.g. gas, kerosene, coal), fertilisers (e.g., nitrates or urea) or soil conditioners. The economics may also be attractive in farming and industry, where considerable cost is experienced in disposing manure, solid wastes and effluents. In these cases, the output can be sold or used to reduce energy and disposal costs, repaying the original capital investment. In cases when the community is charged for treatment of wastes the digestion process may be of great financial importance. When the products do not generate income or reduce cash outflow the economic viability of a biogas plant decreases. For example when cooking fuels such as wood or dung can be collected at zero cost or where the cost of commercial fuel is so low that the market for biogas is limited. Technical, social and economic factors, government support, institutional arrangements, and the general level of commercial activity in the construction of biogas plants and related equipment are highly interrelated [56]. This section focuses on the economic aspects of anaerobic digestion of manure and solid organic wastes, which are currently undergoing new developments and rapid expansion.

4.6.2 Anaerobic digestion of manure

The Danish Biogas Programme [57] is an excellent example of what can be achieved through an ambitious and consistent government policy and is therefore discussed in some detail here. In Denmark 20 centralised biogas plants are operational for treatment of animal manure [58], [59], [60]. The plants mostly employ thermophilic co-digestion (52-53 ºC) with approx. 25% organic wastes mainly from food processing industries. These include animal wastes such as intestinal contents (27%), fat and flotation sludge from food or fodder processing (53%) and wastes from fruit & vegetable processing, dairies and other industries. In the biogas plants manure and organic waste are mixed and digested for 12-25 days. The biogas is utilised for combined heat and power generation. Heat is usually distributed in district heating systems, while electricity is sold to the power grid. The digestate is returned to the farms for use as fertiliser. In 1998 a total of 1 Million tonnes of manure (slurry) were treated in centralised biogas plants and 325,000 tonnes of other wastes, yielding a total of 50.1 Million m^3 biogas at an average gas yield of 37 m^3 per m^3 of biomass [59]. Whereas the normal yield is 20 m^3 of biogas per m^3 of manure slurry, co-digestion thus adds considerably to biogas production and economic feasibility. Techno-economic data for 6 centralised biogas plants in Denmark [59] are summarised in Table 7.

The development of centralised biogas plants in Denmark was made possible in a framework of governmental renewable energy policy, economic incentives and legislative pushes. The latter include the obligation for a 6-9 month manure storage capacity, restrictions on manure application on land and on landfilling of organic wastes. Economic incentives include government investment grants, low interest rate long-term loans (20 years), energy tax exemptions and subsidies on electricity produced from biogas (DKK 0.27 or Euro 0.04 /kWh in 1998; [58]). Another important factor is that heat sales are possible through widely available district heating networks for 6-9 months per year. The plants are operated mostly by co-operatives involving farmers, municipalities and/or private organisations.

The investment costs for the 6 plants in Table 7 (including digesters, storage, transport vehicles and CHP units) range between Euro 870–1,265 /m^3 digester capacity (average: Euro 1,070/m^3) and Euro 48 - 87/tonne processing capacity (average: Euro 65/tonne). This value is low as compared to e.g. a recently built manure processing biogas plant in The Netherlands (25,000 tonnes/year; Euro 160/tonne). The larger scale of the plants (70,000-140,000 tonnes/year) and limited investments for wastewater treatment possibly causes the lower specific investments of the Danish plants. The digested slurry of the Danish plants is returned to the farmers as organic fertiliser, while for the Dutch plant further processing is applied.

The net energy production of the six plants in Table 7 (producing a total of 23.5 million Nm^3 of biogas/year) is estimated at 29,900 MWhe electricity/year and 170 TJ heat/year. The total investment costs per kWe electricity (estimated from Table 7) is around Euro 9,000/kWe. This is however an overestimation because the plants produce heat as well. The total biogas production in centralised plants in Denmark [59] is approx. 50 million Nm^3/ year with an estimated electricity generation of 63,600 MWhe/year and 360,000 TJ /year of heat.

In 1998 most of the operational Danish plants produced an income at or above the break-even level [58]. The income consists of energy sales and gate fees minus operating costs. The total treatment costs (manure and additional wastes) for transport and anaerobic digestion are around Euro 8/m^3 with an income of Euro 7/m^3 from energy sales [60]. Approximately half of the income for energy sales is derived from subsidies (exemption of energy taxation, refunding system). The net treatment costs are Euro 1.4/m^3 [60]. Economic feasibility depends on the co-digestion of food processing wastes, both through the enhanced biogas production and gate fees charged for industrial wastes of Euro 7-13 m^3. According to [60] this is highly competitive –under Danish conditions– with incineration including waste deposit tax (Euro 54-74/tonne) and composting (Euro 40-50/tonne).

TABLE 7. *Techno-economic data for 6 centralised biogas plants in Denmark. Based on [59].*

	Plant location	**Lemvig**	**Thorso**	**Arhus**	**Studsgaard**[1]	**Blabjerg**	**Nysted**
	Units						
Year of operation start-up	--	1992	1994	1995	1996	1996	1998
Animal manure	Tonne/day	362	230	346	230	222	180
Other organic wastes	Tonne/day	75	31	46	36	87	31
Biogas production	Million Nm^3/yr	5.4	2.9	3.8	5.7	3.1	2.6
Biogas production	Nm^3/tonne	38	34	30	65	31	38
Total digester capacity	m^3	7600	4650	8500	6000	5000	5000
Process temperature	Degrees Celsius	52.5	53	38 / 52	52	53.5	38
Gas storage capacity	m^3	5000	2790	370	170	4000	2500
Utilisation of biogas	--	CHP	CHP	CHP	CHP	CHP	CHP/ Boiler
Total energy production biogas 2)	GJ/year	100,980	54,230	71,060	106,590	57,970	48,620
Electricity production 2)	MWh/year	6,872	3,691	4,836	7,254	3,945	3,309
Heat production 2)	GJ/year	38,877	20,879	27,358	41,037	22,318	18,719
Investment costs	Million DKK	55.2	29.1	54.2	55.7	44.1	43.7
Cost index (2000=394) 3)	--	358	368	381	381	381	390
Investment in Euro 2000 (calculated) 4)	Million Euro	8.0	4.1	7.4	7.6	6.0	5.8
Investments per m^3 digester capacity 5)	Euro/m^3	1054	883	869	1265	1202	1164
Investments per tonne capacity 5)	Euro/tonne	56	48	57	87	59	84

1) The Studsgaard plant applies 2.5 hours heating at 60°C prior to digestion.
2) Estimated; assuming 55 vol% methane in biogas (19 MJ/Nm^3, Lower Heating Value); 30 % internal use in the biogas plant; CHP conversion efficiency to electricity 35% and to heat 55%, respectively.
3) Chemical Engineering Plant Cost Index.
4) Recalculated to Euro 2000, using cost indices and exchange rate of 1 DKK = 0.1318 Euro.
5) Including digesters, storage, transport vehicles and CHP units [59].

Manure digestion in The Netherlands. In The Netherlands anaerobic digestion of manure is gaining renewed attention. The largest fraction of produced animal manure is directly recycled as fertiliser. A surplus of 15 million tonnes/year is available for anaerobic digestion [61]. Several small-scale and larger scale biogas plants have started operation in 2001 and 2002 [61]. See Appendix IV for an overview of recent initiatives. A stimulus for this development is the active involvement of utility companies since the end of the 1990's due to the relatively high market price for natural gas and the interest in producing renewable energy.

In The Netherlands the economic benefit of a manure digester can only be achieved with a very high biogas production. In a study on the possibilities of manure co-digestion, it was estimated that the capacity of an installation should be 200 m^3 per day, with a biogas yield of 80 m^3 per tonne of biomass. This can only be achieved when energy rich additives are added such as Fuller's earth or fish-oil sludge [62]. Up till now however, only limited use is made of co-digestion (e.g. with verge grass) to enhance biogas production and economic feasibility. This is mainly caused by incompatible environmental regulations and restrictions on the use of digestates as fertiliser [61], which evidently slows down the development of new plants. There is considerable activity from the side of producers to modify regulations in favour of co-digestion. The attainable electricity production from anaerobic digestion of the total surplus of animal manure in The Netherlands (15 Million tonnes) is estimated at 1,100 GWh (389,000 households). Furthermore a volume of 4 Million tonnes of agricultural wastes is available for co-digestion, which could generate an additional 470 GWh of electricity, for 159,000 households [61].

A regional installation for anaerobic digestion and further processing of pig manure is operational in Elsendorp, The Netherlands since 2001. This installation processes 25,000 tonnes of pig manure per year and produces 1.6 Million kWh of electricity (sufficient for 500 households), 7,500 tonnes of mineral concentrates for use as substitute fertiliser and 17,500 tonnes of clean water. The gate fee for manure is Euro 16-18/m^3, which is similar to alternative manure treatment options [61]. Biogas plant 'De Scharlebelt' at Nijverdal started operation in 2002 [63]. This plant has a capacity of 25,000 tonnes/year (70 tonnes/day) and makes use of thermophilic (50 ºC) co-digestion of pig manure and verge grass. The total digester capacity is 1,500 m^3. The total investment costs were Euro 4 Million (or Euro 160/tonne processing capacity and Euro 6,700/kWe) including storage, CHP unit (600 kWe) and membrane filtration units for effluent post treatment and production of mineral concentrates. The digestate is mechanically separated into a 'humus' fraction and a liquid fraction, which is processed further by means of ultrafiltration and reverse osmosis to produce mineral concentrates and clean water. The biogas is used for the process and the generation of 3 Million kWh of electricity per year (1,000 households). In [64] the investment costs per kWe for biogas plants producing (only) electricity from animal wastes is estimated at Euro 4,400–6,600/kWe (recalculated to Euro 2000) for a 1 MW_e plant.

The cost of biogas produced in small-scale (80 m^3) manure digesting systems on farm level in The Netherlands is estimated at Euro 19/GJ based on data in [38]. Through the use of larger scale systems and economic optimisation a cost reduction to approx. Euro 9/GJ is considered feasible. Calculations based on data from the USA [65] even suggest a possible future biogas cost of Euro 5/GJ for large-scale farms.

4.6.3 Anaerobic digestion of solid biowastes

The main competitors for anaerobic digestion of solid wastes are landfilling and composting. Due to legislation landfilling is already restricted in some countries. Since the European Union is striving towards a substantial reduction of landfilling in the near future[1], composting remains as the main competitor on the longer term. Organic residues from agricultural industry, nowadays used as animal feed, could become available for anaerobic digestion in the future.

Composting is a widely used technique, offering a route for recycling organic matter and nutrients from the organic fraction of municipal solid waste and other biowastes. Composting is however an energy consuming process (approximately 30-35 kWh is consumed per tonne of input waste), while anaerobic digestion is a net energy producing process (100-150 kWh per tonne of input waste) [14]. This evidently makes anaerobic digestion the preferred processing route because it produces renewable energy (biogas) while nutrients are preserved for recycling as well. In a 1994 IEA study [66] the economics of municipal solid waste treatment in The Netherlands by composting and anaerobic digestion were compared based on a 1992 study by Haskoning. The analysis showed somewhat higher treatment costs for anaerobic digestion (Euro 80-35/tonne for a capacity range of 20,000-120,000 tonne/year) than for composting (Euro 60-30/tonne). The study concludes that co-digestion with animal manure could lead to significantly lower costs and that the cost difference between composting and anaerobic digestion is very sensitive to the value of the produced electricity [66]. This illustrates the significance of financial incentives for renewable energy production as a tool for enhancing the competitiveness of biogas plants. Similar cost estimates are provided in [67] for anaerobic digestion of source separated organic fraction of municipal waste (SS-MSW) and mixed waste (MW; separated at the plant) in North America. The capital cost of an SS-MSW facility varies between US $ 635 and $ 245/tonne of design capacity for plants between 10,000 and 100,000 tonnes/year. The capital cost of mixed waste facilities is higher because of the need for a sorting system and ranges between $ 690 and $ 265/tonne. The projected, net annual costs (incl. capital and operating costs, labour and revenues from the sale of biogas

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[1] In the proposed EC Landfill Directive the targets for landfilling (relative to the 1993 situation) are reductions to 50% (2005) and 25% (2010) respectively.

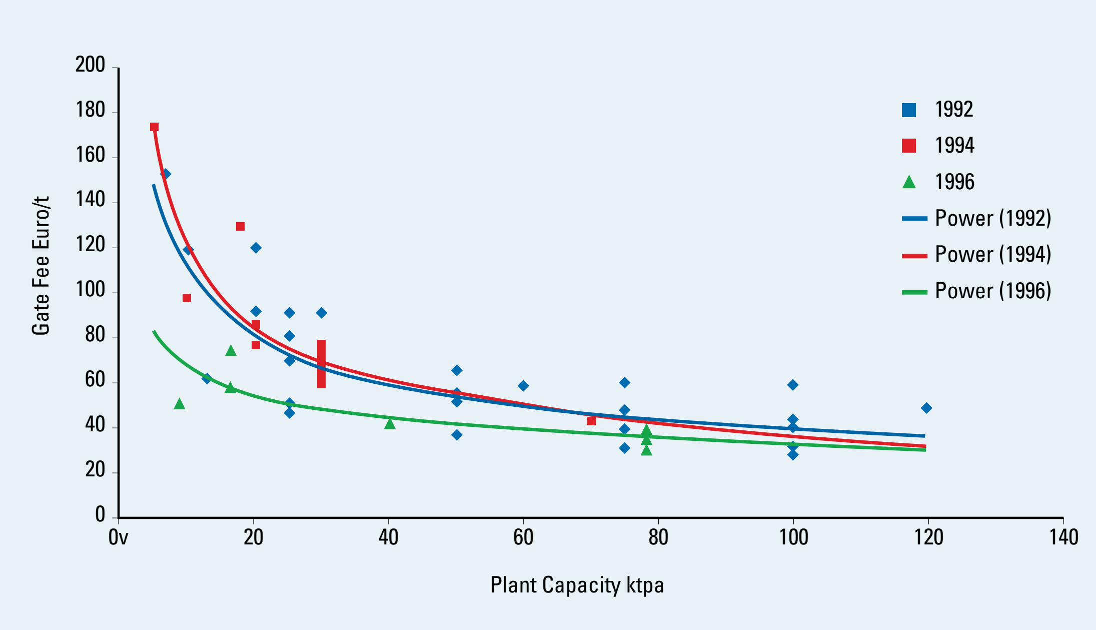

Figure 17. Trends in treatment costs for anaerobic digestion of MSW and biowastes in Europe (ktpa = kilo tonne per year) [42].

and cured digestate for soil conditioning) range between $ 107 and $ 46/tonne for SS-MSW plants and $ 135 - $ 63/tonne for MW plants in the 10,000 to 100,000 ton/year capacity range [67]. The higher costs of anaerobic treatment in comparison to aerobic composting of solid waste are subscribed to the cost of the required water treatment in anaerobic digestion plants in [68]. The latter reference describes a model, consisting of two layered economic and technical sub-models. The results of model calculations indicate that full anaerobic treatment is indeed higher in costs than aerobic composting. Lowest costs are achieved at combined anaerobic/aerobic treatment. Such combined treatment systems are more competitive though the net gas yield will be somewhat lower. Only drastic increases in energy prices or eco-tax would move the system with minimum costs to more anaerobic conversion.

In [47] a detailed techno-economic evaluation is given for an anaerobic digestion system in Germany, processing 26,000 tonnes of fruit and vegetable waste and 4,000 tonnes of green wastes from parks. The biogas is converted in a CHP system to electricity and heat, which is partly used for the process, and an electricity surplus for export to the grid (3,510 MWh/year). The total investment of the plant (including CHP) is 13,2 Million Euro (or Euro 440/tonne processing capacity). The gross treatment costs were estimated at Euro 80/tonne and net at Euro 72/tonne including sales of electricity. According to the study these treatment costs are competitive in the German market compared to modern composting systems [47]. The investments are similar for anaerobic digestion plants for source separated organic waste (SS-MSW) and agro-wastes in The Netherlands which were estimated at Euro 300/tonne capacity (excluding CHP) in the range between 25,000 to 100,000 tonne/year [69]. Assuming a 30% share of CHP in the investment costs the total installed costs (including CHP) would be around Euro 400/tonne processing capacity. The average costs for anaerobic treatment of source separated organic fraction of municipal waste in various systems (Biocel, Valorga, Dranco) were estimated at Euro 75/tonne excluding energy sales [69]. In The Netherlands the composting costs are mainly dependent on the type of material, especially the dry matter concentration. For verge grass for example the costs of composting are on the order of Euro 50/tonne, while the composting costs for woody materials may be somewhat lower i.e. Euro 25-40/tonne. Comparison with the data provided above shows that the costs of anaerobic digestion are still somewhat higher than for composting.

The trends in treatment cost in Europe per tonne of MSW and biowaste for different scales are shown in Figure 17. The figure clearly shows that the costs of anaerobic digestion are increasingly competitive with composting.

Overlooking the international situation there are clear differences between countries in anaerobic digestion plant costs as was shown in [70]. The cost of biogas (per GJ) is highest for Austria and Switzerland, while Germany and Italy are cheapest [70]. The difference between these cheaper plants and more expensive ones has been reduced, due to higher gas yields from the latter.

Economic impacts of digestate utilisation and effluent disposal

The disposal and/or re-use of digestates and liquid effluents originating from anaerobic digestion processes is an important economic issue for all biogas programs. Deposition of liquid and other organic wastes in landfills will be phased out in the near future in the EU. Evidently the recovery and re-use of nutrients (N,P,K) is an important advantage of anaerobic digestion in addition to the recovery of energy because it contributes indirectly to a reduction of greenhouse gas emissions (especially CO_2 and N_2O). In plants treating solid biowastes and/or manure, the solid fraction is in many cases mechanically separated from the process liquor and matured into a compost product. The market value of these compost type products as a soil conditioner or fertiliser depends on the compliance with the governing quality standards especially with respect to the concentration of heavy metals, but also on the guarantee of a pathogen and seed free product. For digestates from the mechanically separated organic fraction of MSW (separation at the plant) the heavy metal content is a critical issue [66]. Digestates from the organic fraction of source separated MSW can comply with the quality standards much more easily.

The digested slurry from manure (co-)digestion may be recycled as fertiliser without much treatment, as is the case in the Danish biogas plants [59]. The digestate is sufficiently sanitised in the thermophilic digestion and care is taken that individual farmers receive a balanced amount of nutrients. Alternatively, the solid fraction of manure digestates may be recovered as a compost-type product while the remaining nutrients are recovered in the form of re-usable mineral concentrates by means of membrane or other technology, as is the case in the new manure processing biogas plants in The Netherlands [62], [63]. In this approach an acceptable water quality for discharge or even re-use is achieved, but investment and maintenance costs will increase considerably. Latter systems are mainly attractive for processing of excess manure, which cannot be used in the direct environment of the farm. Dry minerals can be transported over larger distances. In all processing plants the remaining liquid effluents must be disposed off. Discharge to external (communal or other) wastewater treatment plants may involve considerable costs for transport and treatment charges, depending on the effluent quality [71]. In many cases pre-treatment is required to reduce especially BOD, COD, VFA and nitrogen/ammonia levels prior to disposal. To reduce these costs an on-site effluent post-treatment system may be advantageous. Commonly used techniques include aeration, de-nitrification and reverse osmosis [71].

The role of financial incentives for renewable energy production

As discussed above, financial incentives in the context of renewable energy production play an important role for enhancing the competitiveness of biogas plants, particularly versus composting. A recent overview [72] on the status and promotion of renewable energy in the EU countries provides the following information relevant for biogas plants. The average investment costs for biogas plants for electricity generation have been reduced from Euro 7,000–8,000/kWe (in 1990) to Euro 3,000-5,000/kWe (2000). The investment costs for electricity production from landfill gas have remained constant (Euro 1,000/kWe) over the period 1980-2000. The costs for electricity produced from biogas (2000) range between Euro 0.1 and 0.22/kWh, while electricity from landfill gas is produced for Euro 0.04 - 0.07/kWh. The review also provides an overview of promotion strategies in the EU [72]. These strategies include 'voluntary approaches' such as 'green electricity tariffs' paid by consumers and 'green labels'. Furthermore a number of regulatory, price driven strategies are in place in the EU either 'investment focused' (tax rebates and incentives) or 'generation based'. A widely used form of the latter is the 'feed-in tariff', which is the price per unit of electricity that a utility or supplier has to pay for renewable electricity to private generators ('producers'). In 2000 the highest feed-in tariffs for electricity from biogas and landfill gas were in force in Austria (up to Euro 0.12/kWh), Germany (up to Euro 0.1/kWh), Denmark (Euro 0.08/kWh) and Greece (Euro 0.06/kWh) [72]. As discussed before the biogas program in Denmark has been successful through a combination of legislative measures and financial incentives (tax exemp-tion, investment subsidies). Similarly, the rapid expansion of biogas plants for (especially) manure digestion in Germany in recent years has been greatly stimulated by financial incentives that are guaranteed for long periods (20 years).

4.6.4 Conclusions

From this section the following conclusions can be drawn. Small-scale decentralised biogas plants (e.g on a farm level) can be economically feasible through savings on energy costs and sales of surplus electricity. Larger-scale centralised biogas plants for (co-)digestion of manure (with or without further processing) and/or bio-wastes and municipal solid waste require gate fees for economic viability and depend to a larger extent on sales of energy and other products, such as mineral concentrates or digestates for use as fertiliser. Therefore, in the foreseeable future, gate fees will remain an important element for economic feasibility of larger scale centralised biogas plants. Economic feasibility of larger biogas plants can be optimised through continued technology development including the enhancement of biogas production (co-digestion, pre-treatment) and a reduction of capital investments and operating costs. The past decades have already seen substantial improvements in these two fields. Important elements for enhancing overall economic feasibility for solid waste and manure processing units with anaerobic treatment as the core-technology, are the development of cost effective technologies for effluent post treatment and recovery of mineral concentrates. The combined anaerobic treatment/ aerobic composting of solid waste could be applied to reduce the cost of additional water treatment.

Treatment of wastes in biogas plants is nearing competitiveness towards composting, which will strongly increase renewable energy production. On the short and medium term legislative and financial incentives are an important driver for economic feasibility of biogas plants of all scales. Several measures are already in place including the reduction of landfill deposition and financial incentives in the context of renewable energy policy. Continuation and broadening of support for biogas plants is logical because anaerobic digestion clearly offers advantages over composting, landfilling and incineration in the form of renewable energy production, reduction of greenhouse gas emissions and the possibility for full re-use of nutrients.

It is evident that government programs aimed at increasing the share of renewable energy and greenhouse gas reduction will have an important impact on the expansion of anaerobic digestion.

4.7 International status of anaerobic digestion

Worldwide, more than 125 anaerobic digestion plants are in operation using municipal solid waste or organic industrial waste as their principal feedstock. Their total annual processing capacity is over five Million tonnes, with a potential of generating 600 MW of electricity [42]. Throughout the world, more than 1,300 vendor-supplied systems are in operation or under construction for the treatment of sewage sludge [42]. More than 2,000 anaerobic systems are also in operation for the treatment of industrial wastewater and landfill leachates [26]. Anaerobic digestion systems currently operational in Europe have a total capacity of 1,500 MW, while the potential for 2010 is estimated at 5,300-6,300 MW. Worldwide installed capacity could reach up to 20,000 MW by 2010 [64,77] (Figure 18).

Deployment rates are the highest in Asia, due to governmental programs in China an India including the construction of millions of small-scale digesters. A rapid expansion of anaerobic diges-

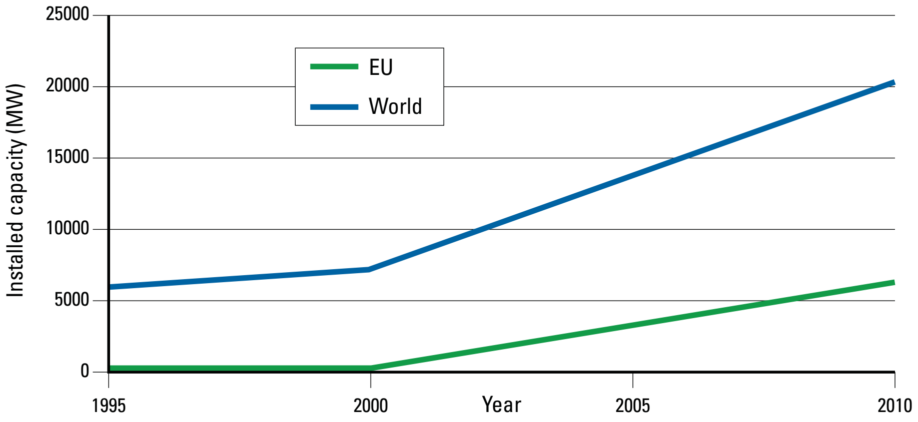

Figure 18. Deployment of anaerobic digestion and estimate of future potential. Adapted from [64, 77].

tion is expected, especially in developing countries, where there is a demand for low cost, reliable plants, which can be locally manufactured [64].

Although anaerobic digestion is a proven technique for a variety of waste streams, there are some barriers to expanded and commercialised biogas production. The most important barriers to overcome are listed in a study on viable energy production and waste recycling from anaerobic digestion of manure and other biomass materials [73]:

- Energy prices and access to energy markets
- Poor data on economics
- Low energy yield
- Bad reputation due to unsuccessful plants
- Lack of information about environmental, agricultural and other non-energy advantages
- Lack of co-operation between relevant sectors/parties
- Legal obstacles

In The Netherlands most renewable energy is derived from incineration of organic waste, while only 9% originates from controlled anaerobic digestion (Table 8 and Figure 19). Not all substrates are suitable for digestion, for example, only the organic part of MSW is suitable, and the digestion of large amounts of wood is also not possible. There are

TABLE 8. *Total amount of energy produced from biomass in The Netherlands in 1998. The number of installations was approx. 1,170. [74].*

			Unit
Consumed by installations	Electric power	518	MW
	Heat	18,665	MW
Avoided amount of primary fossil fuel	Waste incineration	23.3	PJ
	Wood incineration	9.3	PJ
	Landfill gas	2.1	PJ
	Anaerobic Digestion	*3.6*	*PJ*
	Total	38.3	PJ
Delivered as	Electricity	2,743	GWh
	Natural gas	1.9	PJ
	Heat	12.0	PJ
Avoided CO_2 emission		2,451	Ktonne

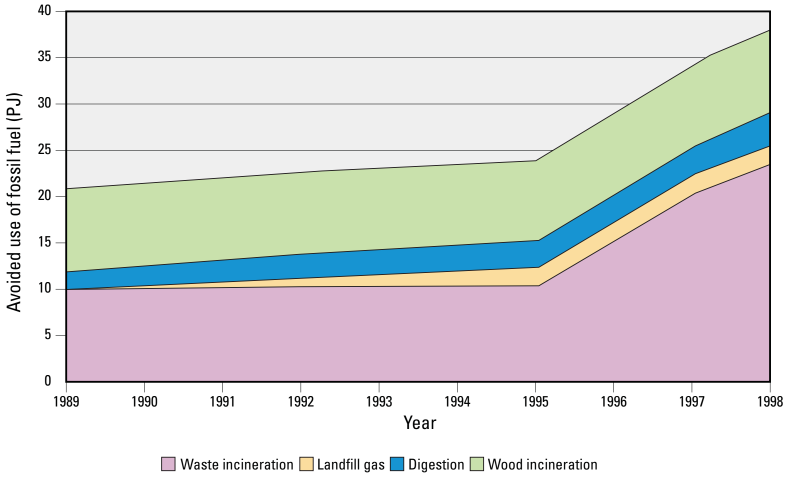

Figure 19. Total amount of energy produced from biomass in The Netherlands over the years 1989-1998 [74].

TABLE 9. *Gas production and energy generation from anaerobic digestion in The Netherlands in 1996 [74].*

Number of installations		**Ca. 225**
Used by installations	Electrical power	21 MW
	Heat	42 MW
Gas production	Total	280 million m^3
	Sewage treatment	191 million m^3
	Industry	78 million m^3
	Manure	5 million m^3
	VFY	5 million m^3
Delivered as	Electricity	106 GWh
	Heat	0.8 PJ
	Natural gas	1.2 PJ
Saved primary energy		3.1 PJ
Avoided CO_2 emission		141 ktonne

sources, which undergo a less favourable treatment in terms of energy consumption, for which controlled anaerobic digestion would be an option. Nowadays most of organic municipal waste (VFY) is composted. Part of the domestic sewage sludge is incinerated without prior digestion. The amount of energy generation from waste is increasing over the years, but the amount contributed by anaerobic digestion remains approximately the same (Figure 19).

Only 2% of biogas produced originates from VFY, as there are only two large plants digesting separated VFY and only one plant (Vagron, Groningen) that treats the organic fraction of MSW in The Netherlands (Figure 20). A second plant (located in Heerenveen) for treating the organic fraction of MSW is currently commencing operation. The contribution of manure digestion is thus far very low (approximately 2%) but is expected to increase in the near future. A combination of these types of waste streams (co-digestion) can lead to higher biogas production [62]. As The Netherlands produces a large amount of manure (Table 10) co-digestion would be a promising technique.

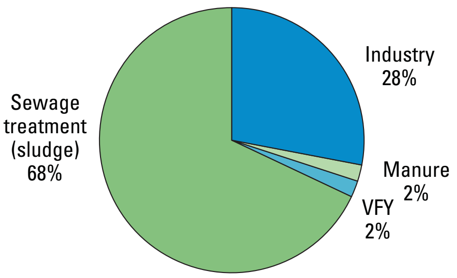

Figure 20. Contribution of different substrates to biogas production (280 million m^3) in The Netherlands in 1996.

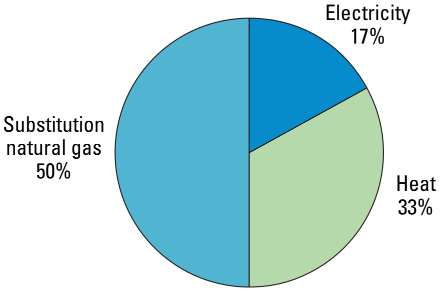

Figure 21. Utilisation of the biogas produced in The Netherlands in 1996 [74].

TABLE 10. *Total manure production in The Netherlands in the period 1994-2000 [75].*

Year	Total produced manure (organic matter). Excluding meadow manure. In kg*1,000
1994	4,208,739
1995	4,263,720
1996	4,206,780
1997	4,125,636
1998	4,075,187
1999	4,039,965
2000	3,906,441

The realisation of 'centralised' treatment facilities will require additional infrastructure, as manure has to be collected from the farm and returned after treatment to the farm for use as fertiliser. In order to prevent the spreading of disease, treatment should include the removal of pathogens by e.g. thermophilic treatment.

Potential feedstocks for anaerobic digestion in The Netherlands are summarised in Table 11. At the moment of the 1,457,000 tonnes of VFY produced each year in The Netherlands, approximately 102,000 tonne is digested and 1,355,000 tonne is treated by other means. Anaerobic treatment of the latter amount could produce 15-23 MW of electricity assuming that one tonne of biowaste can produce approximately 100-150 kWh. Based on the VAGRON process, operating at 52°C, the amount of potential electricity production is 18 MW, accounting for heat loss, electrical conversion and consumption by the plant.

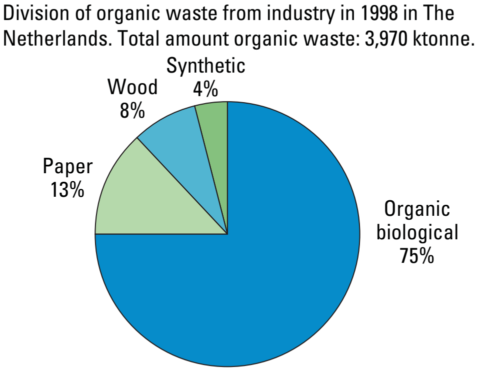

Figure 22. Organic solid waste from industry in The Netherlands in 1998.

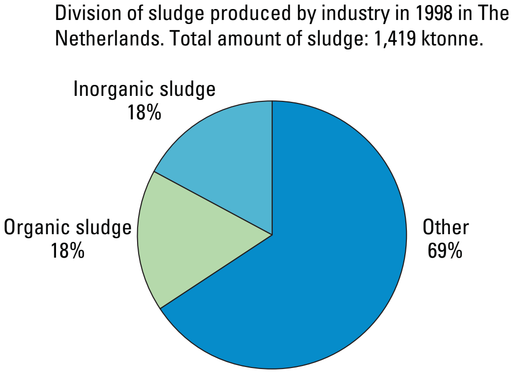

Figure 23. Produced water treatment sludge from industry in The Netherlands in 1998.

TABLE 11. *Possible sources for anaerobic digestion for the generation of methane in The Netherlands [62], updated with values (*) for 2000 [75]*

Source	Waste stream	Production (tonne/year)	Dry matter (%)	Ash content (%)
Municipal waste	VFY	*1,457,000	30	35
Market gardening	Stalks/leaf	231,500	15	10
	Withdrawn vegetables	51,000	6.5	9
	Tomato-stalks	45,000	15	19
	Withdrawn fruit	21,000	12	5
	Withdrawn ornamental plants	485	10	10
	Cabbage leaf	100,000	18	11
	Chicory waste	87,500	20	10
	Roadside grass	600,000	50	20
Maintenance greenery	Waste	150,000	12	5
Maintenance ditches/canals	Organic waste	110,000	9	10
Flavour industry	Slurry from onion oil	11,500	9	15
	Filter bed	4,000	50	
Onion processing industry	Sorting waste	60,000	13	5
Vegetable proc. Industry Fruit	Organic biological	*4,806,000		
proc. Industry	Activated sludge	*3,000		
Pulp and paper Industry	(primary) sludge	*330,000	40	15
Slaughterhouses	sludge grease catcher	10,000	5	
	flotation sludge	*44,000	5	
	slaughter waste/blood/hair	*617,000		
	unborn manure	95,000		
	purification sludge	*8,000	100	
Dairy industry	organic biological	*129,000		
	purification sludge	*1,000	15	
Fish proc. Industry	organic biological	*31,000	100	
	Fuller's earth	15,000	100	28
Oil and grease industry	Purification sludge	*20,000		
Starch and fodder industry	Organic biological	*2,674,000		
Trade/services/etc.	OSS-waste 1)	290,000	20	
Catering/homes/etc.	Swill 2)	107,800	5-7	
Other industrial treatment plants	Purification sludge	1,600,000		
TOTAL		**14,194,300**		

1) organic fraction of office, shops and services waste, like canteen waste
2) organic waste of catering industry and kitchens of homes, barracks, etc

Another potential source for anaerobic digestion is solid waste from industry. In the Food and Beverage industry, producing most organic waste, solid organic waste streams or slurries are mostly used as fodder. The amount of organic waste from industry can be seen in Figure 22 and Figure 23.

4.8 Conclusions and perspectives for further development

Anaerobic digestion is a proven technique and at present applied to a variety of waste (water) streams but world wide application is still limited and a large potential energy source is being neglected. Moreover some potential sources, which are now treated otherwise, are an excellent substrate for anaerobic treatment and could contribute to renewable energy production rather than consuming energy during treatment.

Although The Netherlands is a leading country in the application of anaerobic treatment of industrial and agricultural wastewater, the anaerobic digestion of slurries and solid waste for energy production is scarcely applied. In other European countries like Germany, Austria, Switzerland and Denmark hundreds of installations are currently in operation, showing that technical obstacles and barriers have been overcome. The limited application of anaerobic digestion for energy production from slurries and solid wastes in The Netherlands can, amongst others, be contributed to relatively low natural gas prices. An important difference is moreover the widespread application of co-digestion in other European countries, which significantly improves the economic efficiency of an anaerobic digestion system by increasing the gas production per m^3 reactor content. In The Netherlands, co-digestion is thus far restricted due to legislation. Nowadays a limited range of substrates, mainly plant material, is allowed for co-digestion. However the addition of high-energy substrates like lipids, slaughterhouse wastes or fish-wastes, to manure digesters could substantially increase the gas yield and therefore the economical feasibility of manure digestion. Where co-digestion is applied on a larger scale a large sustainable energy potential becomes available.

Small-scale decentralised biogas plants (e.g. on a farm level) can be economically feasible through savings on energy costs and sales of surplus electricity. Larger-scale centralised biogas plants for (co-) digestion of manure (with or without further processing) and/or bio-wastes and municipal solid waste require gate fees for economic viability and depend to a larger extent on sales of energy and other products, such as mineral concentrates or digestates for use as fertiliser. Maximising the sale of all usable co-products will thus influence the economic merits of an anaerobic treatment system. In the foreseeable future, gate fees will remain an important element for economic feasibility of larger scale biogas plants. Economic feasibility can be optimised through continued technology development including the enhancement of biogas production (co-digestion, pre-treatment) and a reduction of capital investments and operating costs.
In the short and medium term legislative and financial incentives are an important driver for economic feasibility of biogas plants. Besides this, legislation can contribute to a formal consideration of the true cost of various energy options. Several measures are already in place including the reduction of landfill deposition and financial incentives in the context of renewable energy policy. The government now stimulates anaerobic digestion of slurries, as it provides 'green energy'. Another aspect, especially related to the application of controlled anaerobic digestion of animal manure, is the reduction of spontaneous methane emissions that occur during storage of raw manure. In The Netherlands, a large governmental program aimed at the prevention emission of non-CO_2 greenhouse gases such as CH_4 stimulates (among others) the application of animal manure digestion.

The trend in treatment costs in Europe per tonne of MSW and biowaste for different scales shows that the costs of anaerobic digestion are increasingly competitive with composting. Important elements for enhancing overall economic feasibility of solid waste and manure processing units with anaerobic treatment as the core-technology, are the development of cost effective technologies for effluent post treatment and recovery of mineral concentrates. Combined anaerobic treatment/ aerobic composting of solid wastes could be applied to reduce the cost of additional water treatment, though lower gas yields will be the result.

The development of anaerobic conversion techniques has shown that more and more substrates, which originally were not considered for anaerobic treatment, are anaerobically digested today. Diluted, low temperature streams or wastewater with high temperatures and wastewater with toxic and/or xenobiotic components appear to be suitable for anaerobic treatment and lead to stable end products. Anaerobic treatment is a proven technique from an environmental and economic viewpoint. The technology is relatively new, and in many countries application is still in an initial phase. It is of utmost importance to establish demonstration projects in many parts of the world to show the environmental and economic benefits and provide the necessary confidence in the technique. Once demonstrated, anaerobic treatment will become its own advertisement.

The application of anaerobic treatment of domestic sewage is so far limited to tropical countries. Large UASB systems are being applied for this purpose in Asia and South America. Recently the first UASB system for domestic sewage in Africa was installed in Ghana. In low and medium temperature regions the technique is not applied in practice. New developments in high rate anaerobic treatment systems can lead to wider application of anaerobic treatment of conventionally collected domestic sewage even at low temperatures. The strong dilution of domestic sewage in the present collection and transport system of domestic sewage is one of the main difficulties, especially at low temperature conditions. Considering the composition and concentration of the various waste steams produced in the household, illustrates the possibilities of applying new sanitation concepts to enable reuse of energy, water and fertiliser values. Nearly three billion people in the world do not have effective sanitation at their disposal. The central sanitation systems developed in the industrial world are too expensive and too complex to be used world wide. In November 2000, the technical expert consultation on *'Appropriate and Innovative Wastewater Management for Small Communities in EMR countries'*, organised by the World Health Organisation (WHO) in Amman, Jordan concluded that: 'Decentralised Sanitation and Reuse (DeSaR) is the only achievable and environmentally friendly option for countries in the Middle East region.'

The DeSaR concept [76] focuses on the separate collection, transportation and decentralised processing of concentrated domestic waste streams (faeces plus urine or 'night soil' and kitchen waste) and the diluted wastewater streams ('grey water'). Faeces, urine and kitchen waste contain potential energy, which can be recovered by anaerobic digestion, and -in addition- nutrients which can be recovered for use as agricultural fertiliser. Here lies an important key that, with the implementation of DeSaR will allow the energy and nutrient cycle to be closed. The introduction of DeSaR means the transition to a new paradigm. This transition can only become successful when stimulated by governments via for example demonstration projects in new housing estates or large buildings.

4.9 Abbreviations

AF	Anaerobic Filter
AFFR	Anaerobic Fixed Film Reactor
AC	Accumulation reactor
BOD	Biological Oxygen Demand (mg O_2/l)
COD	Chemical Oxygen Demand (mg O_2/l)
CSTR	Continuously Stirred Tank Reactor
DeSaR	Decentralised Sanitation and Re-use
EGSB	Expanded Granular Sludge Bed
F&B	Food and Beverage
FOG	Fat, Oil and Grease (mg/l)
HRT	Hydraulic Retention Time (hours or days)
IC	Internal Circulation reactor
MSW	Municipal Solid Waste
OSS-waste	Organic fraction of Office, Shops and Services waste
OWF	Organic Waste Fraction
p.e.	population equivalent
P&P	Pulp and Paper
RDF	Refuse Derived Fuel
SRT	Sludge Retention Time (hours or days)
SS-MSW	Source Separated Municipal Solid Waste
STP	Sewage Treatment Plant
TS	Total Solids (mg/l) or (%)
TSS	Total suspended solids (mg/l)
TVS	Total Volatile Solids (mg/l)

UASB	Upflow Anaerobic Sludge Bed
VFA	Volatile Fatty Acids (mg/l)
VFY	Vegetable, Fruit and Yard Waste
VS	Volatile Solids (mg/l) or (%)
VSS	Volatile Suspended Solids (mg/l)

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Appendix I Operating anaerobic digestion plants of commercial scale.

All plants have a processing capacity > 2,500 t.p.a. (tonnes/year). MSBW = Municipal Solid Biodegradable Waste; OIW = Organic Industrial Waste; Biosolids = sewage sludge.

Country	Location	Feedstock	System	Scale t.p.a.	Date
Austria	Bergheim-Siggerwiesen	MSBW	Dranco	20,000	1993
	Böheimkirchen	Biowaste, Agricultural	Arge Biogas	5,000	1996
	Eferding	OIW	Entec	7,500	1984
	Feldbach	MSBW	AAT	11,000	1998
	Frastanz	OIW	Entec	17,000	1985
	Graz	MSBW	Dranco		1990
	Hirsdorf	Biowaste, Agricultural	Entec		1994
	Hollabrunn	OIW	Entec	11,000	1983
	Kainsdorf	Biowaste, Agricultural, OIW	Entec	14,000	1995
	Koblach	MSBW	AAT	15,000	1993
	Leesternau	Biowaste	Kompogas	8,000	1997
	Lustenau	Biowaste	Kompogas	10,000	1996
	Mayerhofen	Biowaste, Agricultural	Arge Biogas	2,500	1997
	Roppen	Biowaste	Kompogas	10,000	2001
	Salzburg	OIW, Biosolids	AAT	160,000	1999
	Wels	Biowaste	LINDE	15,000	1996
	Westerwesede	Agricultural, OIW	Entec	5,000	1986
Belgium	Brecht	Biowaste	Dranco	20,000	1992
	Brecht	Biowaste	Dranco	35,000	1999
	Gent	MSBW	AAT	182,000	1999
Canada	Newmarket	Biowaste, OIW	BTA	150,000	2000
Denmark	Arhus	Biowaste, Agricultural, OIW	C.G. Jensen	125,000	1995
	Blaabjerg	Agricultural, OIW	BWSC/Bioscan	113,000	1996
	Blåhøj	Agricultural, OIW	NIRAS	30,000	1997
	Davinde	Agricultural, OIW	Krüger	10,000	1988
	Fangel	Agricultural, OIW	Krüger	53,000	1989
	Filskov	Agricultural, OIW	NIRAS	27,000	1995
	Grindsted	Biowaste, Biosolids	Krüger	40,000	1997
	Hashøj	Agricultural, OIW	Krüger	53,000	1994
	Hodsager	Agricultural, OIW	NIRAS	17,500	1993
	Lemvig	Agricultural, OIW	BWSC	144,000	1992
	Lintrup	Agricultural, OIW	Krüger/Bioscan	190,000	1990
	Nysted	Biowaste, Agricultural, OIW	Krüger	100,000	1998
	Revinge	Agricultural, OIW	Bioscan	15,300	1989
	Ribe	Agricultural, OIW	Krüger	147,000	1990
	Sinding	Biowaste, Agricultural, OIW	Herning Municipal	45,000	1988
	Snertinge	Agricultural, OIW	NIRAS	43,000	1996
	Studsgård	Biowaste, Agricultural, OIW	Herning Municipal	130,000	1996
	Thorsø	Agricultural, OIW	BWSC	110,000	1994
	Vaast-Fjellard	Biowaste, Agricultural, OIW	NIRAS	55,000	1997
	Vegger	Agricultural, OIW	JYSK Biogas	19,000	1986
	Vester Hjermitslev	Agricultural, OIW	Krüger	17,000	1984

Country	Location	Feedstock	System	Scale t.p.a.	Date
Finland	Vaasa	MSBW	Waasa/Wabio	15,000	1994
France	Amiens	MSBW	Valorga	85,000	1988
Germany	Alzey	Biowaste	Kompogas	24,000	2000
	Baden-Baden	Biowaste, Biosolids	BTA	5,000	1993
	Bassum	Grey waste	Dranco	16,500	1997
	Behringen	Agricultural, OIW	LINDE	23,000	1996
	Bottrop	Biowaste	Wabio	6,500	1995
	Braunschweig	Biowaste	Kompogas	20,000	1997
	Buchen	Grey waste	ISKA	20,000	2001
	Dietrichsdorf-Volkenschwand	Biowaste, OIW	BTA	17,000	1995
	Ellert	Biowaste	Entec	5,000	1997
	Engelskirchen	Biowaste	Valorga	35,000	1998
	Erkheim	Biowaste, OIW	BTA	11,000	1997
	Finsterwald	Biowaste, Agricultural	Schwartung UHDE	90,000	1995
	Frankfurt	Biowaste	Kompogas	15,000	2000
	Freiburg	Biowaste	Valorga	36,000	1999
	Fürstenwalde	Biowaste, OIW	LINDE	85,000	1998
	Ganderkesee	Biowaste	ANM	3,000	1995
	Gröden-Schraden	Agricultural, OIW	Haase Energietechnic	110,000	1995
	Groß Mühlingen	Biowaste, Agricultural, OIW	DSD	42,000	1996
	Groß Pankow	Agricultural, OIW	Alusteel/NNR	7,700	1994
	Heppenheim	Biowaste, OIW	LINDE	33,000	1999
	Herten	Biowaste	IMK	18,000	1998
	Himmelkron	Agricultural, OIW	AAT	2,800	1995
	Herschfelde	OIW	AAT	3,600	1997
	Kahlenburg	MSBW	Wehrle/Biopercolat	20,000	2001
	Karlsruhe	Biowaste	BTA	800	1996
	Kaufbeuren	Biowaste, OIW	BTA	2,500	1992
	Kempten	Biowaste	Kompogas	10,000	1995
	Kirchstockach	Biowaste	BTA	25,000	1997
	Lemgo	Biowaste, OIW	LINDE	38,000	2000
	Michaelisdonn	Agricultural, OIW	Krüger	35,000	1995
	München	Biosolids, OIW	Schwarting UHDE	86,400	1987
	München/Eitting	Biowaste	Kompogas	24,000	1997
	Münster	Biowaste	BTA/Roediger	20,000	1997
	Neukirchen	Agricultural, Biowaste	AAT	55,000	1998
	Nordhausen	Biowaste	Haase	16,000	1999
	Oldenburg	Agricultural, OIW	Krüger	20,000	1992
	Pastitz/Rügen	Agricultural, OIW	Bioplan	100,000	1997
	Radeberg	Biosolids, Biowaste, OIW	LINDE	56,000	1999
	Regensburg	Biowaste	TBW/Biocomp	12,000	1996
	Roding	Biowaste	AAT	7,000	1996
	Sagard/Island Rügen	Biowaste, Agricultural, OIW	LINDE	48,000	1996
	Schwabach	Biowaste	BTA/ATU	12,000	1996
	Schwanebeck	Biowaste, Agricultural	Haase	50,000	1999
	Simmern	Biowaste	Kompogas	10,000	1997
	Wadern-Lockweiler	Biowaste, OIW	BTA	20,000	1998
	Wittmund	Agricultural, OIW	Krüger	120,000	1996
	Zobes	Biowaste, Agricultural, OIW	DSD	20,000	1986

Country	Location	Feedstock	System	Scale t.p.a.	Date
Indonesia	Bogor	OIW	Dranco		1986
Italy	Bastia/Brettona	Agricultural, OIW	RPA	30,000	1982
	Bellaria	MSBW	Ionics Italbia	4,000	1988
	Marsciano	Agricultural, OIW	SPI	300,000	1988
	Thiene	Agricultural, OIW	KIKlos	60,000	1990
Japan	Kagoshima	Biowaste, Agricultural	Dranco		1998
Netherlands	Breda	Niowaste	Paques	10,000	1992
	Breda	OIW	Paques	25,000	1987
	Groningen	Grey waste	CiTec	85,000	1999
	Lelystad	Biowaste	Heidemij, Biocel	35,000	1997
	Tilburg	Biowaste	Valorga	52,000	1994
Spain	La Coruña	OIW	AAT	34,000	1993
Sweden	Borås	MSBW	YIT/VMT	9,000	1995
	Helsingborg	Agricultural, OIW	NSR	20,000	1996
	Kalmar	Agricultural, OIW	VBB Viak/Läckeby	25,000	1998
	Kil	MSBW	CiTec	3,000	1998
	Kristianstad	MSBW, Agricultural, OIW	Krüger	73,000	1997
	Laholm	Agricultural, OIW	Krüger	37,000	1992
	Linköping	Agricultural, OIW	Purac	105,000	1997
	Uppsala	MSBW, Agricultural, OIW	VBB Viak/Läckeby	30,000	1997
	Vanersborg	MSBW	YIT/VMT	20,000	2000
Switzerland	Aarberg	Biowaste	Dranco	11,000	1997
	Baar	Biowaste	LINDE	6,000	1994
	Bachenbülach	Biowaste, Yard	Kompogas	10,000	1994
	Frauenfeld	Biowaste, OIW	Rom-OPUR	15,000	1999
	Geneva	Biowaste	Valorga	10,000	2000
	Muhen	Agricultural, OIW	LINDE	5,000	1986
	Niederuzwil	Biowaste	Kompogas	13,000	1997
	Otelfingen	Biowaste	Kompogas	12,000	1996
	Rümlang	Biowaste, Yard	Kompogas	8,500	1992
	Samstagern	Biowaste, Yard	Kompogas	10,000	1995
	Villeneuve	Biowaste	Dranco	10,000	1999
	Volketswil	Biowaste, Yard	Kompogas	10,000	2000
	Vuiteboeuf	Agricultural, OIW	LINDE	6,900	1986
	Wädenswil	OIW	Entec	5,000	1997
Ukraine	Zaporozhstol	Agricultural, OIW	Krüger	12,000	1992
USA	Greenboro, NC	Yard wastes	DEES	30,000	2000
	Moorfield, WV	Biowaste/Agricultural/Biosolids	Enviro-control	3,000	1996
	Princeton, NC	Agricultural, OIW	DEES	3,500	1999

Appendix II Characteristics of various types of industrial wastewater [41].

Branch of industry	**Raw wastewater characteristics**		**(max) Anaerobic degradability**	**Reference**
	BOD_5 (mg/l)	COD (mg/l)	(m^3 CH_4/kg COD removed)	
Food & Beverage				
Slaughterhouses				
Meat	450-1500		IWACO 1991	
	500-1500		IWACO 1991	
	490-650	1500-2200		Sayed 1987
"low strength"	1100	1440	82.7% of CODtot inf.	Nunez and Martinez 1999
"medium strength"	1400	2500	82.7% of CODtot inf.	Nunez and Martinez 1999
"high strength"	2400	4200	82.7% of CODtot inf.	Nunez and Martinez 1999
Poultry	250-3700			IWACO 1991
	350-500			IWACO 1991
	370-620			Middelbrooks 1979
	1000-2100	1500-3500		Eremektar, Cokgor et al. 1999
meat processing	100-300			IWACO 1991
	1300			IWACO 1991
		1880		Campos, Foresti et al. 1986
Dairy				
Dairy products	300-10000			IWACO 1991
	480-2500			IWACO 1991
		52000	0.36	Hickey and Owens 1981
		12000-35000	0.27-0.3	Li, Sutton et al. 1982
		2200-10000	0.1-0.395	Boening and Larsen 1982
		3560-4250	0.08-0.29	Viraraghavan, Kikkeri et al 1990
cheese whey	12000	20000	0.55	Yilmazer and Yenigun 1999
egg processing	3000-3200	5000-6900		Middlebrooks 1979
	150			IWACO 1991
	1400-3000			IWACO 1991
Fish				
Fish processing	350-3500			IWACO 1991
	5000			IWACO 1991
		20000-53600		Veiga, Mendez et al. 1992
	3000-4200	4800-6400		Nair 1990
	84-32700			Middlebrooks, 1979
		1830-12230	75-80% of CODtot inf.	Palenzuela 1983
		18500-55200	75-95% of CODtot inf.	Soto, Mendez et al. 1991
Tuna		29500	72-76% of CODtot inf.	Punal and Lema 1999
mussel cooking		18500	86-95% of CODtot inf.	Punal and Lema 1999
Pulp & Paper				
Pulping				
Thermo mechanical pulping		1000-4500	67-87% of CODtot inf.	Sierra-Alvarez 1999
Chemo-thermo mechanical pulping	6000-13000		Sierra-Alvarez 1999	
Chemical		5000-6000	85-90% of CODtot inf.	Kroiss, Svardal et al. 1985
paper making	1500	3000		Hulshoff-Pol and Lettinga 1986

Appendix II (continued) Characteristics of various types of industrial wastewater.

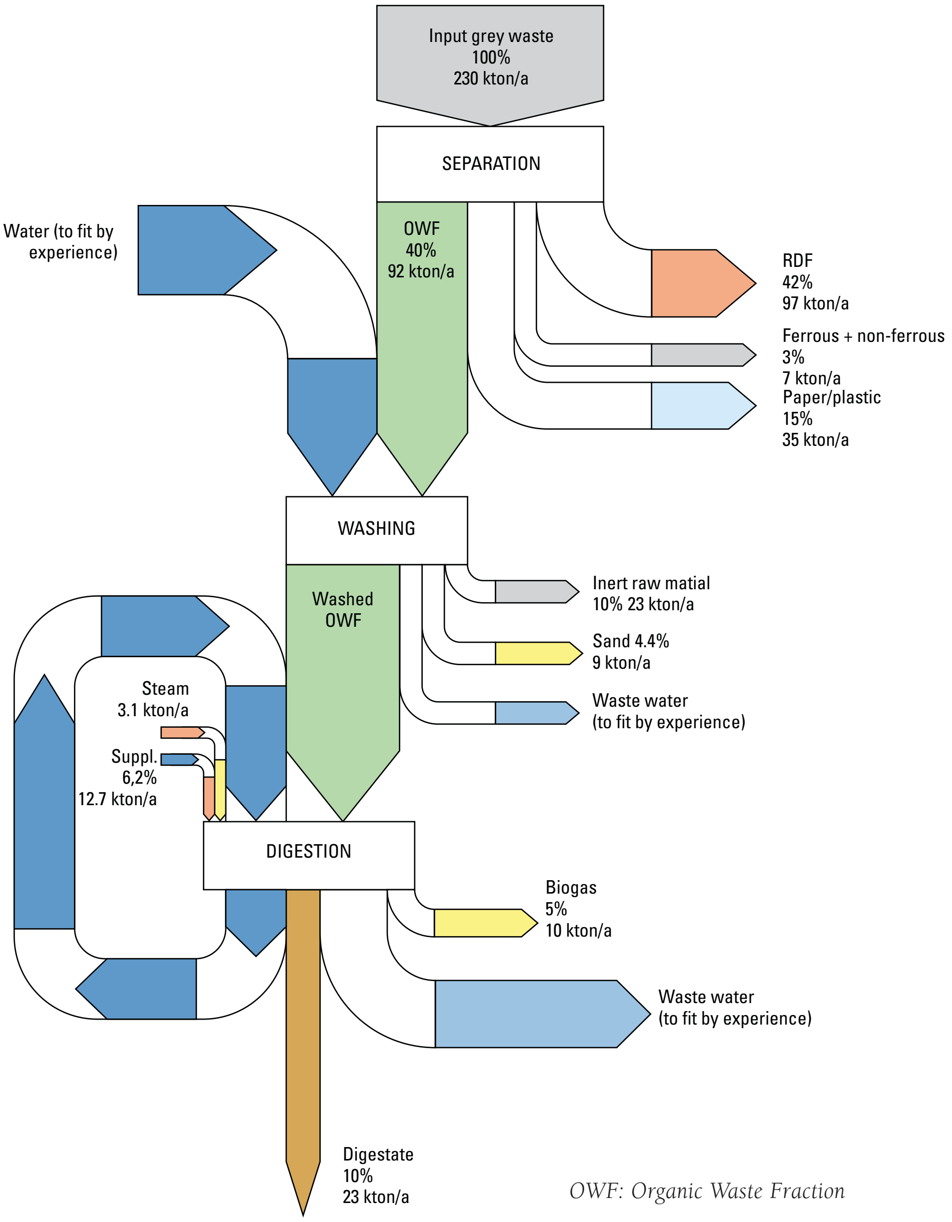
Branch of industry	Raw wastewater characteristics		(max) Anaerobic degradability	Reference
	BOD$_5$ (mg/l)	COD (mg/l)	(m^3 CH$_4$/kg COD removed)	
Grain & Starch				
Grain	240-500			IWACO 1991
	225-14600			Middlebrooks, 1979
Maize	5700-11900	5300-24900		Krings, Donnerhack et al. 1992
	8100			IWACO 1991
Patatoes	4900	5700		Krings et al 1992
	500-1500			IWACO 1991
Wheat	18600-37500	21700-52500		Krings et al 1992
	4700			IWACO 1991
Sugar				
	250			IWACO 1991
	930			IWACO 1991
	15-1900	60-4400		Barnes, Forster et al. 1984
		480-9000	0.33	Chen, Li et al. 1982
	4000-6000	6000-10000		Austermann Haun, Meyer et al. 1999
Edible oil and Grease				
	100-2000			IWACO 1991
	500-5000			IWACO 1991
	500-6700			Middlebrooks, 1979
	31300-31800	69700-72000	75-80% of CODtot inf.	Tsonis and Grigoropoulos 1988
Beverages/Distilleries				
Soft drink	180-370			IWACO 1991
	380-660			Middlebrooks, 1979
	500	1400	89%COD/96% BOD removal	Craveiro, Soares et al. 1986
		6000	0.41	Hickey and Owens 1981
Breweries	750			IWACO 1991
	750-3000			IWACO 1991
	1600			Middlebrooks, 1979
	1500	2500	92%COD/99% BOD removal	Craveiro et al. 1986
	1500	2300		Austermann-Haun et al 1999
Distilleries	100			IWACO 1991
	15000			IWACO 1991
	480-9000			Middlebrooks, 1979
	19800-25000	45000-65000		Costa, Rocha et al. 1986
		8700-9500	0.348	Frostell 1982
		12000-20000		Austermann-Haun et al 1999
Fruit/Vegetable processing				
Fruit/Vegetable processing	1900			IWACO 1991
Vegetables	200-800			IWACO 1991
Potato		5000	80% of CODtot infl.	Zoutberg and Eker 1999
Coffee	1250			IWACO 1991
		9400-15000		Calzada, Rolz et al. 1986
	3000	4000		Hajipakkos 1982

Appendix III Energy and mass balance of the VAGRON installation treating grey waste

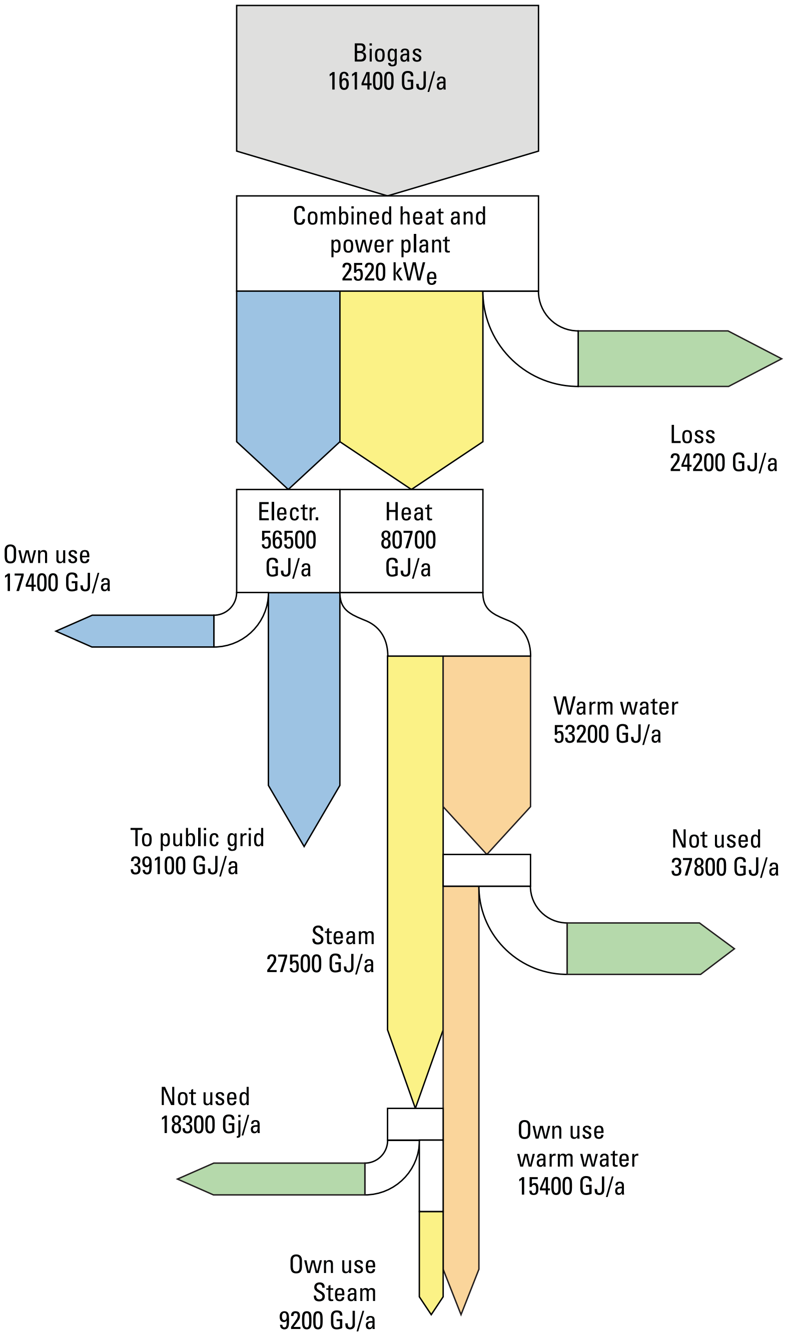
Adapted from the Vagron website
http://www.vagron.nl/html/nl/massa.htm.

Separating waste results in the reuse of more than 50% of the incoming waste stream. Only about 42% of the waste is incinerated.

A total of 2.5 MWe of electric energy is produced, about one third of which is used internally. The remainder is supplied to the public electricity network. About 3.6 MWh of thermal energy is produced, which is used to heat process water and create steam. In total, the conversion of bio-methane into energy (electricity + heat) achieves an energy yield of 85%.



OWF: Organic Waste Fraction


Biogas
161400 GJ/a
Combined heat and power plant
2520 kW$_e$
Loss
24200 GJ/a
Electr.
56500
GJ/a
Heat
80700
GJ/a
Own use
17400 GJ/a
Warm water
53200 GJ/a
To public grid
39100 GJ/a
Not used
37800 GJ/a
Steam
27500 GJ/a
Not used
18300 Gj/a
Own use
warm water
15400 GJ/a
Own use
Steam
9200 GJ/a

Appendix IV Operational manure digesters in The Netherlands [61,63].

Location	Description of project	Capacity	Start-up date
Elsendorp	Regional digestion of 25,000 tonnes of pig manure per year. The installation produces 1,600 GWh of electricity/yr, 7,500 tonnes of mineral concentrates and 17,500 tonnes of clean water. Supplier: Biorek Agro B.V.	1,600 GWhe / year	September 2001
Goutum	Farm-scale digester at Praktijkcentrum Nije Bosma Zathe. Capacity: 900 m^3 cattle manure /year (+ 900 planned). Co-digestion with green maize. Supplier: Biogas Nederland BV		February 2001
Nijverdal	Regional, thermophilic (co)digestion of 22,000/3,000 tonne pig manure / roadside grass at "De Scharlebelt". Biogas is used for Combined Heat and Power production. Composting of solid fraction of digestate. The liquid fraction is processed by ultra filtration and reverse osmosis to produce mineral concentrates and clean water. Supplier: Wolter & Dros Biowatt B.V.	600 kWe CHP – unit	February 2002
Miste	Farm-scale co-digestion of 1,000 m^3/year pig and chicken manure with green maize, cabbage and fodder beets. J. Leemkuil. Supplier: WISA.		January 2001
Sterksel	Digester at testing farm for pigs (Praktijkcentrum Sterksel). Capacity 4,500 m^3/year pig manure. Biogas is used in 37 kWe CHP unit. Supplier: Ecogas international B.V.	37 kW CHP unit	January 2002