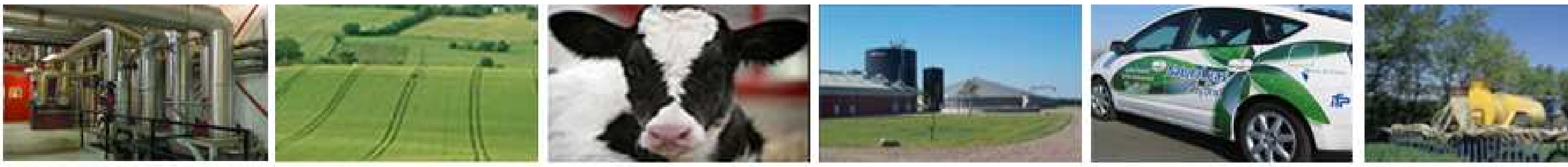
biogas

HANDBOOK



BiG>East
Biogas for Eastern Europe

Colophon

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The editor thanks all the authors, the reviewers and the two talented students for their contribution to the handbook and for the great team work.

Teodorita Al Seadi
October 2008

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Foreword

One of the main environmental problems of today's society is the continuously increasing production of organic wastes. In many countries, sustainable waste management as well as waste prevention and reduction have become major political priorities, representing an important share of the common efforts to reduce pollution and greenhouse gas emissions and to mitigate global climate changes. Uncontrolled waste dumping is no longer acceptable today and even controlled landfill disposal and incineration of organic wastes are not considered optimal practices, as environmental standards hereof are increasingly stricter and energy recovery and recycling of nutrients and organic matter is aimed.

Production of biogas through anaerobic digestion (AD) of animal manure and slurries as well as of a wide range of digestible organic wastes, converts these substrates into renewable energy and offers a natural fertiliser for agriculture. At the same time, it removes the organic fraction from the overall waste streams, increasing this way the efficiency of energy conversion by incineration of the remaining wastes and the biochemical stability of landfill sites.

AD is a microbiological process of decomposition of organic matter, in the absence of oxygen, common to many natural environments and largely applied today to produce biogas in airproof reactor tanks, commonly named digesters. A wide range of micro-organisms are involved in the anaerobic process which has two main end products: biogas and digestate. Biogas is a combustible gas consisting of methane, carbon dioxide and small amounts of other gases and trace elements. Digestate is the decomposed substrate, rich in macro- and micro nutrients and therefore suitable to be used as plant fertiliser.

The production and collection of biogas from a biological process was documented for the first time in United Kingdom in 1895 (METCALF & EDDY 1979). Since then, the process was further developed and broadly applied for wastewater treatment and sludge stabilisation. The energy crisis in the early '70s brought new awareness about the use of renewable fuels, including biogas from AD. The interest in biogas has further increased today due to global efforts of displacing the fossil fuels used for energy production and the necessity of finding environmentally sustainable solutions for the treatment and recycling of animal manure and organic wastes.

Biogas installations, processing agricultural substrates, are some of the most important applications of AD today. In Asia alone, millions of family owned, small scale digesters are in operation in countries like China, India, Nepal and Vietnam, producing biogas for cooking and lighting. Thousands of agricultural biogas plants are in operation in Europe and North America, many of them using the newest technologies within this area, and their number is continuously increasing. In Germany alone, more than 3.700 agricultural biogas plants were in operation in 2007.

In line with the other biofuels, biogas from AD is an important priority of the European transport and energy policy, as a cheap and CO_2-neutral source of renewable energy, which offers the possibility of treating and recycling a wide range of agricultural residues and by-products, in a sustainable and environmentally friendly way. At the same time, biogas brings along a number of socio-economic benefits for the society as a whole as well as for the involved stakeholders.

The enlargement of the EU brought new members to the family of European biogas producers, which will benefit from implementing biogas technologies for renewable energy production while mitigating important environmental pollution problems and enhancing sustainable development of rural communities.

Teodorita Al Seadi and Dominik Rutz

Aim and how to use the handbook

One of the major problems of stakeholders interested in biogas technologies is the lack of a single source of information about the AD process, the technical and non-technical aspects of planning, building and operating biogas plants as well as about biogas and digestate utilisation. This kind of information is scattered throughout literature, thus a unified approach and information clearinghouse was needed.

This biogas handbook is intended as a "*how to approach*"-guide, giving basic information about biogas from AD, with the main focus on agricultural biogas plants. The handbook is therefore primarily addressed to farmers and to future agricultural biogas plant operators, but also to the overall biogas stakeholders.

The handbook consists of three main parts. The first part, **"What is biogas and why do we need it",** provides basic information about biogas technologies, describing the microbiological process of AD and its main applications in the society, the utilisation of biogas and digestate and the technical components of a biogas plant. The second part, entitled **"How to get started"**, shows how to approach the planning and building of a biogas plant, highlighting also the safety elements to be taken into consideration as well as the possible costs and benefits of such a plant. This part is supported by an EXCEL calculation tool (see the attached CD on the inner back cover). The third part consists of **"Annexes"** and includes explanation of terms, conversion units, abbreviations, literature and the address list of authors and reviewers.

Throughout the handbook, decimal comma is used.

What is biogas and why do we need it?

1 Advantages of biogas technologies

The production and utilisation of biogas from AD provides environmental and socio-economic benefits for the society as a whole as well as for the involved farmers. Utilisation of the internal value chain of biogas production enhances local economic capabilities, safeguards jobs in rural areas and increases regional purchasing power. It improves living standards and contributes to economic and social development.

1.1 Benefits for the society

1.1.1 Renewable energy source

The current global energy supply is highly dependent on fossil sources (crude oil, lignite, hard coal, natural gas). These are fossilised remains of dead plants and animals, which have been exposed to heat and pressure in the Earth's crust over hundreds of millions of years. For this reason, fossil fuels are non-renewable resources which reserves are being depleted much faster than new ones are being formed

The World’s economies are dependent today of crude oil. There is some disagreement among scientists on how long this fossil resource will last but according to researchers, the “peak oil production”* has already occurred or it is expected to occur within the next period of time (figure 1.1).

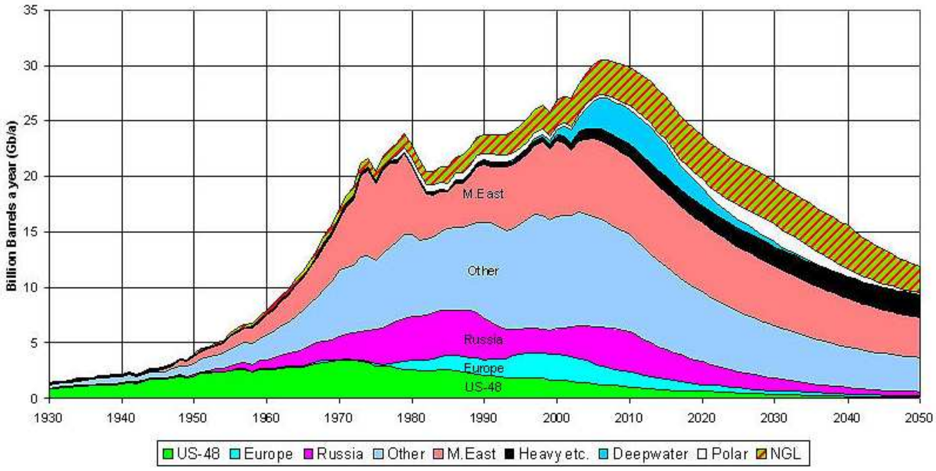

Figure 1.1 Scenario of World oil production and “peak oil” (ASPO 2008)

**The peak oil production is defined as “the point in time at which the maximum rate of global production of crude oil is reached, after which the rate of production enters its terminal decline”*

Unlike fossil fuels, biogas from AD is permanently renewable, as it is produced on biomass, which is actually a living storage of solar energy through photosynthesis. Biogas from AD will not only improve the energy balance of a country but also make an important contribution to the preservation of the natural resources and to environmental protection.

1.1.2 Reduced greenhouse gas emissions and mitigation of global warming

Utilisation of fossil fuels such as lignite, hard coal, crude oil and natural gas converts carbon, stored for millions of years in the Earth's crust, and releases it as carbon dioxide (CO_2) into the atmosphere. An increase of the current CO_2 concentration in the atmosphere causes global warming as carbon dioxide is a greenhouse gas (GHG). The combustion of biogas also releases CO_2. However, the main difference, when compared to fossil fuels, is that the carbon in biogas was recently up taken from the atmosphere, by photosynthetic activity of the plants. The carbon cycle of biogas is thus closed within a very short time (between one and several years). Biogas production by AD reduces also emissions of methane (CH_4) and nitrous oxide (N_2O) from storage and utilisation of untreated animal manure as fertiliser. The GHG potential of methane is higher than of carbon dioxide by 23 fold and of nitrous oxide by 296 fold. When biogas displaces fossil fuels from energy production and transport, a reduction of emissions of CO_2, CH_4 and N_2O will occur, contributing to mitigate global warming.

1.1.3 Reduced dependency on imported fossil fuels

Fossil fuels are limited resources, concentrated in few geographical areas of our planet. This creates, for the countries outside this area, a permanent and insecure status of dependency on import of energy. Most European countries are strongly dependent on fossil energy imports from regions rich in fossil fuel sources such as Russia and the Middle East. Developing and implementing renewable energy systems such as biogas from AD, based on national and regional biomass resources, will increase security of national energy supply and diminish dependency on imported fuels.

1.1.4 Contribution to EU energy and environmental targets

Fighting the global warming is one of the main priorities of the European energy and environmental policies. The European targets of renewable energy production, reduction of GHG emission, and sustainable waste management are based on the commitment of the EU member states to implement appropriate measures to reach them. The production and utilisation of biogas from AD has the potential to comply with all three targets at the same time.

1.1.5 Waste reduction

One of the main advantages of biogas production is the ability to transform waste material into a valuable resource, by using it as substrate for AD. Many European countries are facing enormous problems associated with overproduction of organic wastes from industry, agriculture and households. Biogas production is an excellent way to comply with increasingly restrictive national and European regulations in this area and to utilise organic wastes for energy production, followed by recycling of the digested substrate as fertiliser. AD can also contribute to reducing the volume of waste and of costs for waste disposal.

1.1.6 Job creation

Production of biogas from AD requires work power for production, collection and transport of AD feedstock, manufacture of technical equipment, construction, operation and maintenance of biogas plants. This means that the development of a national biogas sector contributes to the establishment of new enterprises, some with significant economic potential, increases the income in rural areas and creates new jobs.

1.1.7 Flexible and efficient end use of biogas

Biogas is a flexible energy carrier, suitable for many different applications. One of the simplest applications of biogas is the direct use for cooking and lighting, but in many countries biogas is used nowadays for combined heat and power generation (CHP) or it is upgraded and fed into natural gas grids, used as vehicle fuel or in fuel cells.

1.1.8 Low water inputs

Even when compared to other biofuels, biogas has some advantages. One of them is that the AD process needs the lowest amount of process water. This is an important aspect related to the expected future water shortages in many regions of the world.

1.2 Benefits for the farmers

1.2.1 Additional income for the farmers involved

Production of feedstock in combination with operation of biogas plants makes biogas technologies economically attractive for farmers and provides them with additional income. The farmers get also a new and important social function as energy providers and waste treatment operators.

1.2.2 Digestate is an excellent fertiliser

A biogas plant is not only a supplier of energy. The digested substrate, usually named digestate, is a valuable soil fertiliser, rich in nitrogen, phosphorus, potassium and micronutrients, which can be applied on soils with the usual equipment for application of liquid manure. Compared to raw animal manure, digestate has improved fertiliser efficiency due to higher homogeneity and nutrient availability, better C/N ratio and significantly reduced odours.

1.2.3 Closed nutrient cycle

From the production of feedstock to the application of digestate as fertiliser, the biogas from AD provides a closed nutrient and carbon cycle (Figure 1.2). The methane (CH_4) is used for energy production and the carbon dioxide (CO_2) is released to the atmosphere and re-uptaken by vegetation during photosynthesis. Some carbon compounds remain in the digestate, improving the carbon content of soils, when digestate is applied as fertiliser. Biogas production can be perfectly integrated into conventional and organic farming, where digestate replaces chemical fertilisers, produced with consumption of large amounts of fossil energy.

1.2.4 Flexibility to use different feedstock

Various types of feedstock can be used for the production of biogas: animal manure and slurries, crop residues, organic wastes from dairy production, food industries and agro-industries, wastewater sludge, organic fraction of municipal solid wastes, organic wastes from households and from catering business as well as energy crops. Biogas can also be collected, with special installations, from landfill sites.

One main advantage of biogas production is the ability to use “wet biomass” types as feedstock, all characterised by moisture content higher than 60–70% (e.g. sewage sludge, animal slurries, flotation sludge from food processing etc.). In recent years, a number of energy crops (grains, maize, rapeseed), have been largely used as feedstock for biogas production in countries like Austria or Germany. Besides energy crops, all kinds of agricultural residues, damaged crops, unsuitable for food or resulting from unfavourable growing and weather conditions, can be used to produce biogas and fertiliser. A number of animal by-products, not suitable for human consumption, can also be processed in biogas plants. A more detailed description of biomass types, frequently used as substrates for AD can be found in Chapter 3.1.

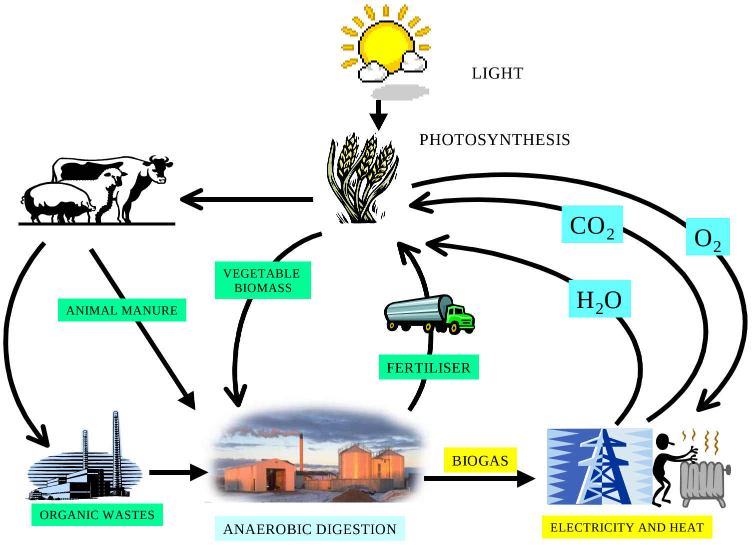

Figure 1.2 The sustainable cycle of biogas from AD (AL SEADI 2001)

1.2.5 Reduced odours and flies

Storage and application of liquid manure, animal dung and many organic wastes are sources of persistent, unpleasant odours and attract flies. AD reduces these odours by up to 80% (Figure 1.3). Digestate is almost odourless and the remaining ammonia odours disappear shortly after application as fertiliser.

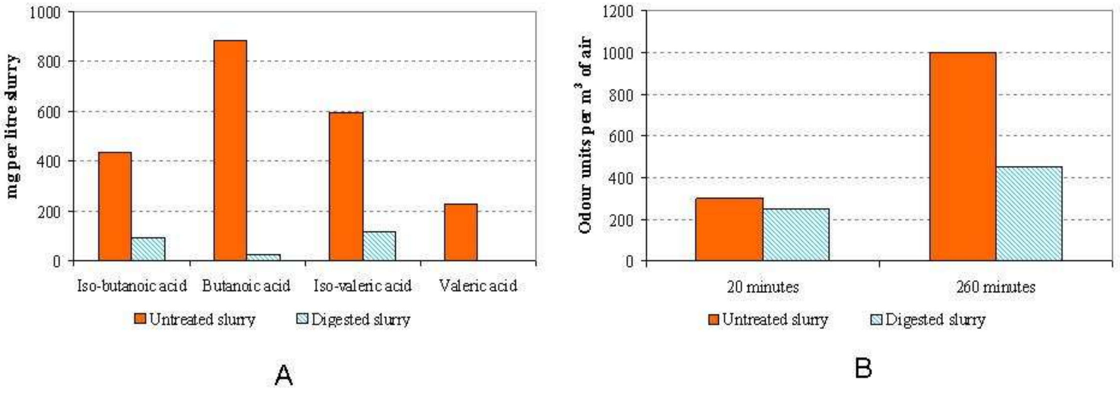

Figure 1.3 A: Concentration of odours (smelling volatile fatty acids) in untreated slurry and in digested slurry
B: Odour concentration in air samples collected above the fields, after application of untreated slurry and digested slurry (HANSEN et al. 2004)

1.2.6 Veterinary safety

Application of digestate as fertiliser, compared to application of untreated manure and slurries, improves veterinary safety. In order to be suitable for use as fertiliser, digestate is submitted to a controlled sanitation process. Depending of the type of feedstock involved, sanitation can be provided by the AD process itself, through a minimum guaranteed retention time of the substrate inside the digester, at thermophilic temperature, or it can be done in a separate process step, by pasteurisation or by pressure sterilisation. In all cases, the aim of sanitation is to inactivate pathogens, weed seeds and other biological hazards and to prevent disease transmission through digestate application.

2 Biogas from AD - state of art and potential

2.1 AD state of art and development trends

The world markets for biogas increased considerably during the last years and many countries developed modern biogas technologies and competitive national biogas markets throughout decades of intensive RD&D complemented by substantial governmental and public support. The European biogas sector counts thousands of biogas installations, and countries like Germany, Austria, Denmark and Sweden are among the technical forerunners, with the largest number of modern biogas plants. Important numbers of biogas installations are operating also in other parts of the world. In China, it is estimated that up to 18 million rural household biogas digesters were operating in 2006, and the total Chinese biogas potential is estimated to be of 145 billion cubic meters while in India approximately 5 million small-scale biogas plants are currently in operation. Other countries like Nepal and Vietnam have also considerable numbers of very small scale, family owned biogas installations.

Most biogas plants in Asia are using simple technologies, and are therefore easy to design and reproduce. On the other side of the Atlantic, USA, Canada and many Latin American countries are on the way of developing modern biogas sectors and favourable political frameworks are implemented alongside, to support this development.

Important research efforts combined with full scale experience are carried out around the world, aiming to improve the conversion technologies, the operational and process stability and performance. New digesters, new combinations of AD substrates, feeding systems, storage facilities and other equipment are continuously developed and tested.

Alongside the traditional AD feedstock types, dedicated energy crops for biogas production were introduced in some countries and the research efforts are directed towards increasing productivity and diversity of energy crops and assessment of their biogas potential. Cultivation of energy crops brought about new farming practices and new crop rotation systems are about to be defined, where intercropping and combined crop cultivation are subject of intensive research as well.

Utilisation of biogas for combined heat and power production (CHP) is a standard application for the main part of the modern biogas technologies in Europe. Biogas is also upgraded and used as renewable biofuel for transport in countries like Sweden, Switzerland and Germany, where networks of gas upgrading and filling stations are established and operating. Biogas upgrading and feeding into natural gas grid is a relatively new application but the first installations, in Germany and Austria, are feeding “biomethane” into the natural gas grids. A relatively new utilisation of biogas, in fuel cells, is close to the commercial maturity in Europe and USA.

Integrated production of biofuels (biogas, bioethanol and biodiesel) alongside with food and raw materials for industry, known as the concept of biorefineries, is one important research area today, where biogas provides process energy for liquid biofuel production and uses the effluent materials of the other processes as feedstock for AD. The integrated biorefinery concept is expected to offer a number of advantages related to energy efficiency, economic performance and reduction of GHG emissions. A number of biorefinery pilot projects have been implemented in Europe and around the world, and full scale results will be available in the years to come.

2.2 Biogas potential

The existing biomass resources on our planet can give us an idea of the global potential of biogas production. This potential was estimated by different experts and scientists, on the base of various scenarios and assumptions. Regardless the results of these estimations, the overall conclusion was always, that only a very small part of this potential is utilised today, thus there is a real possibility to increase the actual production of biogas significantly. The European Biomass Association (AEBIOM) estimates that the European production of biomass based energy can be increased from the 72 million tones (Mtoe) in 2004 to 220 Mtoe in 2020. The largest potential lies in biomass originating from agriculture, where biogas is an important player. According to AEBIOM, up to 20 to 40 million hectares (Mha) of land can be used for energy production in the European Union alone, without affecting the European food supply.

Figure 2.1 European natural gas grid and potential corridors (yellow) suitable for biogas production and biomethane injection (THRÄN et al. 2007)

The German Institute for Energy and Environment states that the biogas potential in Europe is as high enough to be feasible to replace the total consumption of natural gas, by injection of upgraded biogas (biomethane) into the existing natural gas grid (Figure 2.1). The estimation of biogas potential in Europe depends on the different factors and assumptions which are included in the calculations such as agricultural availability of land which does not affect food production, productivity of energy crops, methane yield of feedstock substrates and energy efficiency of biogas end use.

3 More about anaerobic digestion (AD)

AD is a biochemical process during which complex organic matter is decomposed in absence of oxygen, by various types of anaerobic microorganisms. The process of AD is common to many natural environments such as the marine water sediments, the stomach of ruminants or the peat bogs. In a biogas installation, the result of the AD process is the *biogas* and the *digestate.* If the substrate for AD is a homogenous mixture of two or more feedstock types (e.g. animal slurries and organic wastes from food industries), the process is called "co–digestion" and is common to most biogas applications today.

3.1 Substrates for AD

A wide range of biomass types can be used as substrates (feedstock) for the production of biogas from AD (Figures 3.1, 3.2 and 3.3). The most common biomass categories used in European biogas production are listed below and in Table 3.1.

- Animal manure and slurry
- Agricultural residues and by-products
- Digestible organic wastes from food and agro industries (vegetable and animal origin)
- Organic fraction of municipal waste and from catering (vegetable and animal origin)
- Sewage sludge
- Dedicated energy crops (e.g. maize, miscanthus, sorghum, clover).

Table 3.1 Biowastes, suitable for biological treatment, according to EUROPEAN WASTE CATALOGUE, 2007.

Waste Code	Waste description	
02 00 00[1]	Waste from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	Waste from agriculture, horticulture, aquaculture, forestry, hunting and fishing
		Waste from the preparation and processing of meat, fish and other foods of animal origin
		Wastes from the fruit, vegetables, cereals, edible oils, cocoa, tea and tobacco preparation and processing: conserve production; yeast and yeast extract production, molasses preparation and fermentation
		Wastes from sugar processing
		Wastes from the dairy products industry
		Wastes from the baking and confectionery industry
		Wastes from the production of alcoholic and non-alcoholic beverages (except coffee, tea and cocoa)
03 00 00	Wastes form wood processing and the production of panels and furniture, pulp, paper and cardboard	Wastes from wood processing and the production of panels and furniture
		Wastes from pulp, paper and cardboard production and processing
04 00 00	Waste from the leather, fur and textile industries	Wastes from the leather and fur industry
		Wastes from the textile industry
15 00 00	Waste packing; absorbents, wiping cloths, filter materials and protective clothing not otherwise specified	Packaging (including separately collected municipal packaging waste)
19 00 00	Waste from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use	Wastes from anaerobic treatment of waste
		Wastes from waste water treatment plants not otherwise specified
		Wastes from the preparation of water intended for human consumption or water for industrial use
20 00 00	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Separately collected fractions (except 15 01)
		Garden and park wastes (including cemetery waste)
		Other municipal wastes

1) The 6-digit code refers to the correspondent entry in the European Waste Catalogue (EWC) adopted by the European Commissions.

Figure 3.1 Municipal solid waste supplied to a German biogas plant (RUTZ 2008)

Figure 3.2 Catering waste (RUTZ 2007)

Figure 3.3 Maize silage (RUTZ 2007)

Utilisation of animal manure and slurries as feedstock for AD has some advantages due to their properties:

- The naturally content of anaerobic bacteria
- The high water content (4-8% DM in slurries), acting as solvent for the other co-substrates and ensuring proper biomass mixing and flowing
- The cheap price
- The high accessibility, being collected as a residue from animal farming

During recent years, a new category of AD feedstock has been tested and introduced in many countries, the dedicated energy crops (DEC), which are crops grown specifically for energy, respectively biogas production. DEC can be herbaceous (grass, maize, raps) but also woody crops (willow, poplar, oak), although the woody crops need special delignification pre-treatment before AD.

The substrates for AD can be classified according to various criteria: origin, dry matter (DM) content, methane yield etc. Table 3.2 gives an overview on the characteristics of some digestible feedstock types. Substrates with DM content lower than 20% are used for what is called wet digestion (wet fermentation). This category includes animal slurries and manure as well as various wet organic wastes from food industries. When the DM content is as high as 35%, it is called dry digestion (dry fermentation), and it is typical for energy crops and silages. The choice of types and amounts of feedstock for the AD substrate mixture depends on their DM content as well as the content of sugars, lipids and proteins.

Table 3.2 The characteristics of some digestible feedstock types (AL SEADI 2001)

Type of feedstock	Organic content	C:N ratio	DM %	VS % of DM	Biogas yield $m^3 * kg^{-1}$ VS	Unwanted physical impurities	Other unwanted matters
Pig slurry	Carbohydrates, proteins, lipids	3-10	3-8	70-80	0,25-0,50	Wood shavings, bristles, water, sand, cords, straw	Antibiotics, disinfectants
Cattle slurry	Carbohydrates, proteins, lipids	6-20	5-12	80	0,20-0,30	Bristles, soil, water, straw, wood	Antibiotics, disinfectants, NH_4^+
Poultry slurry	Carbohydrates, proteins, lipids	3-10	10-30	80	0,35-0,60	grit, sand, feathers	Antibiotics, Disinfectants, NH_4^+,
Stomach/intestine content	Carbohydrates, proteins, lipids	3-5	15	80	0,40-0,68	Animal tissues	Antibiotics, disinfectants
Whey	75-80% lactose 20-25% protein	-	8-12	90	0,35-0,80	Transportation impurities	
Concentrated whey	75-80% lactose 20-25% protein	-	20-25	90	0,80-0,95	Transportation impurities	
Flotation sludge	65-70% proteins 30-35%lipids	-				Animal tissues	Heavy metals, disinfectants, organic pollutants
Ferment. slops	Carbohydrates	4-10	1-5	80-95	0,35-0,78	Non-degradable fruit remains	
Straw	Carbohydrates, lipids	80-100	70-90	80-90	0,15-0,35	Sand, grit	
Garden wastes		100-150	60-70	90	0,20-0,50	Soil, cellulosic components	Pesticides
Grass		12-25	20-25	90	0,55	Grit	Pesticides
Grass silage		10-25	15-25	90	0,56	Grit	
Fruit wastes		35	15-20	75	0,25-0,50		
Fish oil	30-50% lipids	-					
Soya oil/margarine	90% vegetable oil	-					
Alcohol	40% alcohol	-					
Food remains			10	80	0,50-0,60	Bones, plastic	Disinfectants
Organic household waste						Plastic, metal, stones, wood, glass	Heavy metals, organic pollutants
Sewage sludge							Heavy metals, organic pollutants

Substrates containing high amounts of lignin, cellulose and hemicelluloses can also be co-digested, but a pre-treatment is usually applied in this case, in order to enhance their digestibility.

The potential methane yield is one of the important criteria of evaluation of different AD substrates (Figure 3.4). It is noticeable, that animal manure has a rather low methane yield. This is why, in praxis, animal manure is not digested alone, but mixed with other co-substrates, with high methane yield, in order to boost the biogas production. Common co-substrates, added for co-digestion with manure and slurries, are oily residues from food, fishing and feed industries, alcohol wastes, from brewery and sugar industries, or even specially cultivated energy crops.

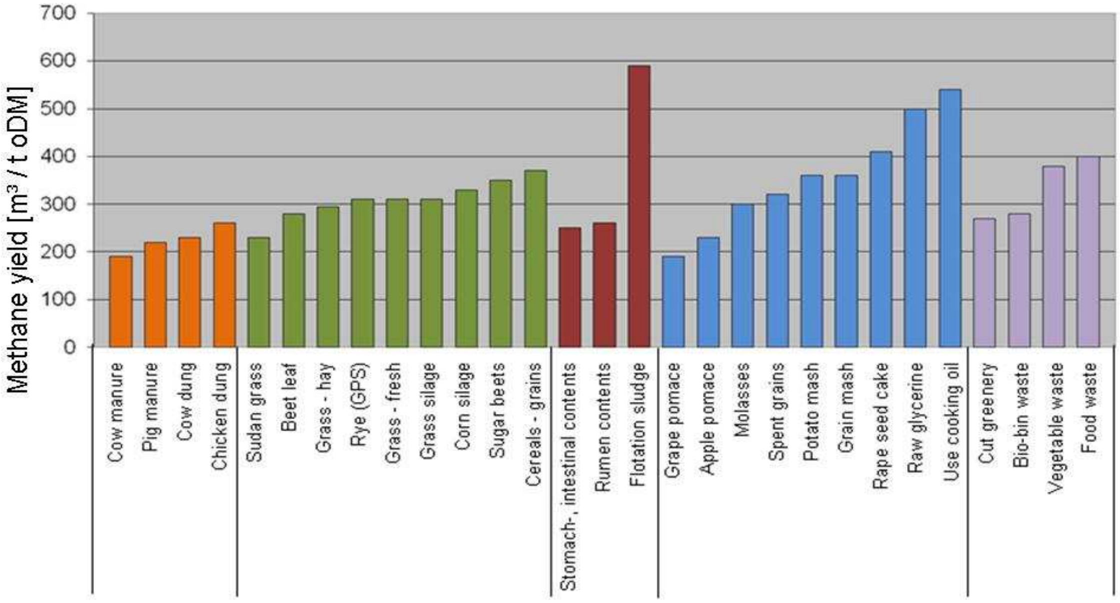

Figure 3.4 Benchmarks for specific methane yields (PRAßL 2007)

The feedstock for AD could contain chemical, biological or physical contaminants. Quality control of all feedstock types is essential in order to ensure a safe recycling of digestate as fertiliser. The potential contaminants for some common AD feedstock types are shown in Table 3.3. Wastes of animal origin require special attention if supplied as substrate for AD. Regulation 1774/2002 of the European Parliament laid down health rules regarding handling and utilisation of animal by-products not intended for human consumption.

Table 3.3 Potential load of problem-materials, contaminants and pathogens of some AD feedstock categories

		Risk			
		Safe	***Hygienic risks***	***Contains problem materials***	***Risks of contaminants***
Feedstock	***Communal residue material***	Greenery, grass cuttings		Biowaste, Roadside greenery	
	Industrial residue materials	Vegetable waste, mash, pommace, etc.	Expired foodstuff, foods with transport damage		Residue from vegetable oil production
	Agricultural residues	Fluid dung, solid dung			Cu and Zn
		Beet leaves, straw			
	Renewable raw materials	Corn silage, grass silage			
	Slaughter waste		Rumen, stomach-intestinal contents, separated fats, blood flour, etc.		Separated- fats
	Miscellaneous		Industrial kitchen waste, household waste		

The regulation sets out minimum rules and measures to be implemented, indicating which types of animal by-products are allowed to be processed in biogas plants and in which conditions. The regulation is available in full text at http://europa.eu/scadplus/leg/en/lvb/f81001.htm.

3.2 The biochemical process of AD

As previously stated, AD is a microbiological process of decomposition of organic matter in absence of oxygen. The main products of this process are biogas and digestate. Biogas is a combustible gas, consisting primarily of methane and carbon dioxide. Digestate is the decomposed substrate, resulted from the production of biogas.

During AD, very little heat is generated in contrast to aerobic decomposition (in presence of oxygen), like it is the case of composting. The energy, which is chemically bounded in the substrate, remains mainly in the produced biogas, in form of methane.

The process of biogas formation is a result of linked process steps, in which the initial material is continuously broken down into smaller units. Specific groups of micro-organisms are involved in each individual step. These organisms successively decompose the products of the previous steps. The simplified diagram of the AD process, shown in Figure 3.5, highlights the four main process steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

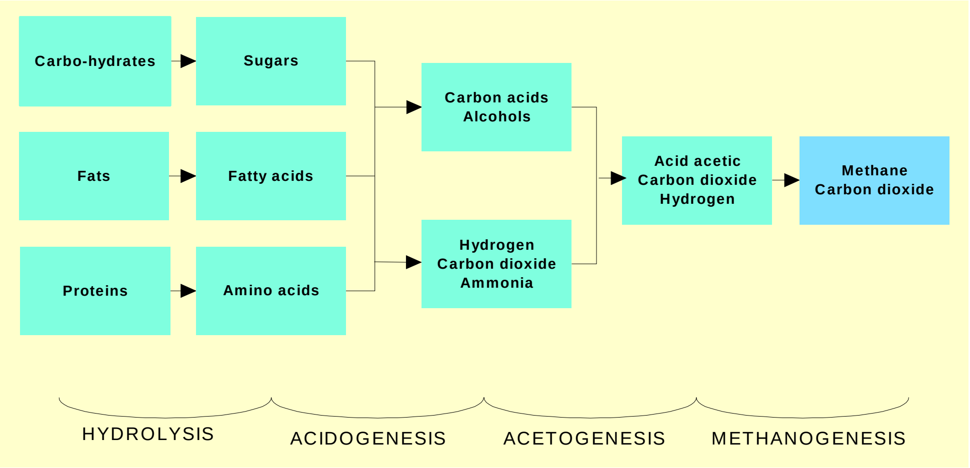

Figure 3.5 The main process steps of AD (AL SEADI 2001)

The process steps quoted in Figure 3.5 run parallel in time and space, in the digester tank. The speed of the total decomposition process is determined by the slowest reaction of the chain. In the case of biogas plants, processing vegetable substrates containing cellulose, hemi-cellulose and lignin, hydrolysis is the speed determining process. During hydrolysis, relatively small amounts of biogas are produced. Biogas production reaches its peak during methanogenesis.

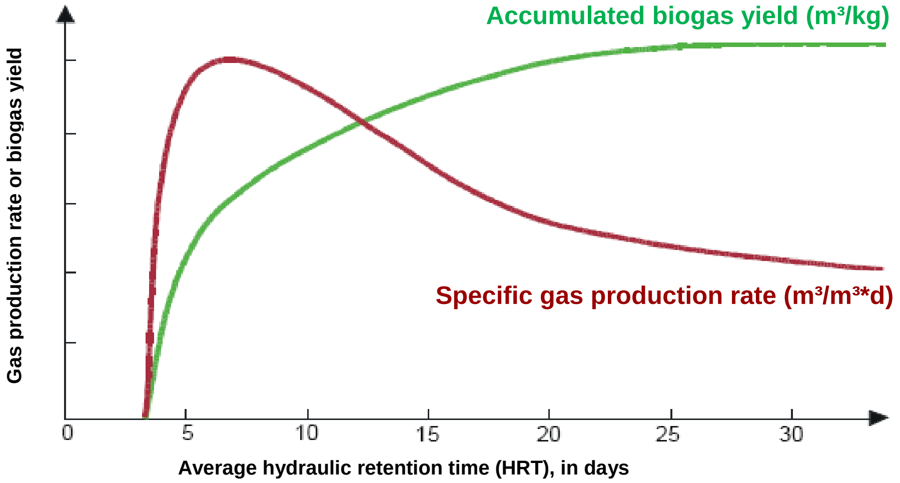

Figure 3.6 Biogas production after addition of substrate –batch test (LfU 2007)

3.2.1 Hydrolysis

Hydrolysis is theoretically the first step of AD, during which the complex organic matter (polymers) is decomposed into smaller units (mono- and oligomers). During hydrolysis, polymers like carbohydrates, lipids, nucleic acids and proteins are converted into glucose, glycerol, purines and pyridines. Hydrolytic microorganisms excrete hydrolytic enzymes, converting biopolymers into simpler and soluble compounds as it is shown below:

$$\textit{Lipids} \xrightarrow{\textit{lipase}} \textit{fatty acids, glycerol}$$

$$\textit{Polysaccharide} \xrightarrow{\text{cellulase, cellobiase, xylanase, amylase}} \textit{monosaccharide}$$

$$\textit{Proteins} \xrightarrow{\textit{protease}} \textit{amino acids}$$

A variety of microorganisms is involved in hydrolysis, which is carried out by exoenzymes, produced by those microorganisms which decompose the undissolved particulate material. The products resulted from hydrolysis are further decomposed by the microorganisms involved and used for their own metabolic processes.

3.2.2 Acidogenesis

During acidogenesis, the products of hydrolysis are converted by acidogenic (fermentative) bacteria into methanogenic substrates. Simple sugars, amino acids and fatty acids are degraded into acetate, carbon dioxide and hydrogen (70%) as well as into volatile fatty acids (VFA) and alcohols (30%).

3.2.3 Acetogenesis

Products from acidogenesis, which can not be directly converted to methane by methanogenic bacteria, are converted into methanogenic substrates during acetogenesis. VFA and alcohols are oxidised into methanogenic substrates like acetate, hydrogen and carbon dioxide. VFA, with carbon chains longer than two units and alcohols, with carbon chains longer than one unit, are oxidized into acetate and hydrogen. The production of hydrogen increases the hydrogen partial pressure. This can be regarded as a „waste product“ of acetogenesis and inhibits the metabolism of the acetogenic bacteria. During methanogenesis, hydrogen is converted into methane. Acetogenesis and methanogenesis usually run parallel, as symbiosis of two groups of organisms.

3.2.4 Methanogenesis

The production of methane and carbon dioxide from intermediate products is carried out by methanogenic bacteria. 70% of the formed methane originates from acetate, while the remaining 30% is produced from conversion of hydrogen (H) and carbon dioxide (CO_2), according to the following equations:

$$\textit{Acetic acid} \xrightarrow{\text{methanogenic bacteria}} \textit{methane} + \textit{carbon dioxide}$$
$$\textit{Hydrogen} + \textit{carbon dioxide} \xrightarrow{\text{methanogenic bacteria}} \textit{methane} + \textit{water}$$

Methanogenesis is a critical step in the entire anaerobic digestion process, as it is the slowest biochemical reaction of the process. Methanogenesis is severely influenced by operation conditions. Composition of feedstock, feeding rate, temperature, and pH are examples of factors influencing the methanogenesis process. Digester overloading, temperature changes or large entry of oxygen can result in termination of methane production.

3.3 AD parameters

The efficiency of AD is influenced by some critical parameters, thus it is crucial that appropriate conditions for anaerobic microorganisms are provided. The growth and activity of anaerobic microorganisms is significantly influenced by conditions such as exclusion of oxygen, constant temperature, pH-value, nutrient supply, stirring intensity as well as presence and amount of inhibitors (e.g. ammonia). The methane bacteria are fastidious anaerobes, so that the presence of oxygen into the digestion process must be strictly avoided.

3.3.1 Temperature

The AD process can take place at different temperatures, divided into three temperature ranges: psychrophilic (below 25°C), mesophilic (25°C – 45°C), and thermophilic (45°C – 70°C). There is a direct relation between the process temperature and the HRT (Table 3.4).

Table 3.4 Thermal stage and typical retention times

Thermal stage	Process temperatures	Minimum retention time
psychrophilic	< 20 °C	70 to 80 days
mesophilic	30 to 42 °C	30 to 40 days
thermophilic	43 to 55 °C	15 to 20 days

The temperature stability is decisive for AD. In practice, the operation temperature is chosen with consideration to the feedstock used and the necessary process temperature is usually provided by floor or wall heating systems, inside the digester. Figure 3.7 shows the rates of relative biogas yields depending on temperature and retention time.

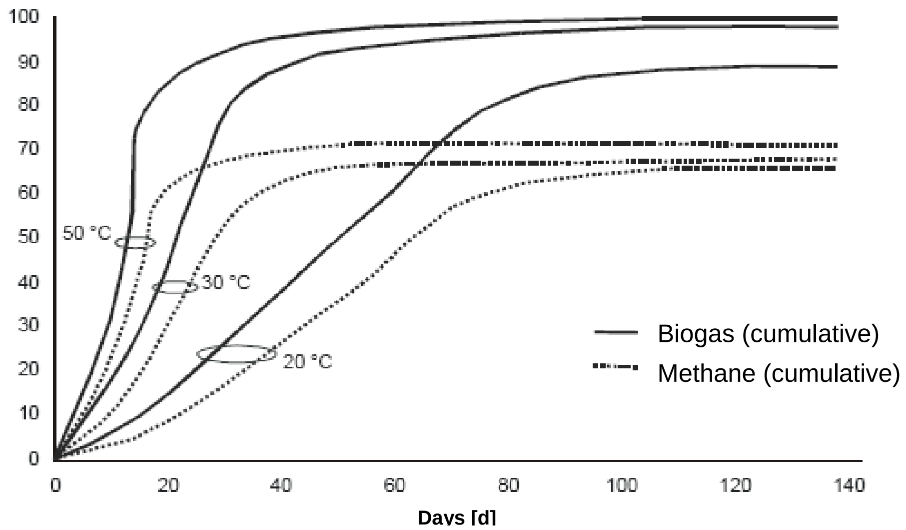

Figure 3.7 Relative biogas yields, depending on temperature and retention time (LfU 2007)

Many modern biogas plants operate at thermophilic process temperatures as the thermophilic process provides many advantages, compared to mesophilic and psychrophilic processes:

- effective destruction of pathogens
- higher grow rate of methanogenic bacteria at higher temperature
- reduced retention time, making the process faster and more efficient
- improved digestibility and availability of substrates
- better degradation of solid substrates and better substrate utilisation
- better possibility for separating liquid and solid fractions

The thermophilic process has also some disadvantages:

- larger degree of imbalance
- larger energy demand due to high temperature
- higher risk of ammonia inhibition

Operation temperature influences the toxicity of ammonia. Ammonia toxicity increases with increasing temperature and can be relieved by decreasing the process temperature. However, when decreasing the temperature to 50°C or below, the growth rate of the thermophilic microorganisms will drop drastically, and a risk of washout of the microbial population can occur, due to a growth rate lower than the actual HRT (ANGELIDAKI 2004). This means that a well functioning thermophilic digester can be loaded to a higher degree or operated at a lower HRT than an e.g. mesophilic one because of the growth rates of thermophilic organisms (Figure 3.8). Experience shows that at high loading or at low HRT, a thermophilic operated digester has higher gas yield and higher conversion rates than a mesophilic digester.

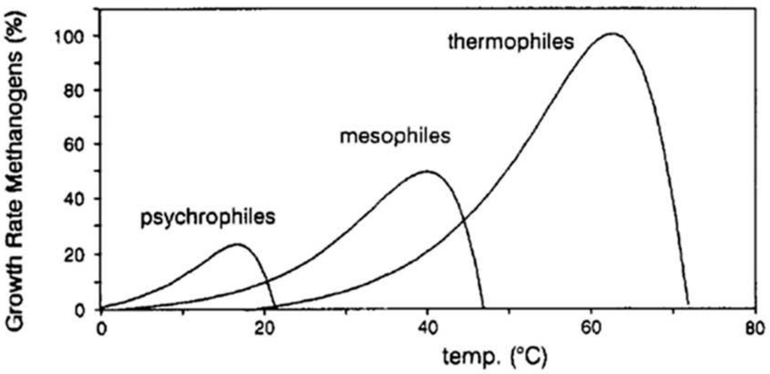

Figure 3.8 Relative growth rates of methanogens (ANGELIDAKI 2004)

The solubility of various compounds (NH_3, H_2, CH_4, H_2S and VFA) also depends on the temperature (Table 3.5). This can be of great significance for materials which have an inhibiting effect on the process.

Table 3.5 The relation between temperature and the solubility in water of some gases (ANGELIDAKI 2004)

Gas	Temperature (°C)	Solubility mmol/l water	Changed solubility 50°C-35°C
H_2	35 50	0,749 0,725	3,3 %
CO_2	35 50	26,6 19,6	36 %
H_2S	35 50	82,2 62,8	31 %
CH_4	35 50	1,14 0,962	19 %

The viscosity of the AD substrate is inversely proportional to temperature. This means that the substrate is more liquid at high temperatures and the diffusion of dissolved material is thus facilitated. Thermophilic operation temperature results in faster chemical reaction rates, thus better efficiency of methane production, higher solubility and lower viscosity.

The higher demand for energy in the thermophilic process is justified by the higher biogas yield. It is important to keep a constant temperature during the digestion process, as temperature changes or fluctuations will affect the biogas production negatively. Thermophilic bacteria are more sensitive to temperature fluctuation of +/-1°C and require longer time to adapt to a new temperature, in order to reach the maximum methane production. Mesophilic bacteria are less sensitive. Temperature fluctuations of +/- 3°C are tolerated, without significant reductions in methane production.

3.3.2 pH-values and optimum intervals

The pH-value is the measure of acidity/alkalinity of a solution (respectively of substrate mixture, in the case of AD) and is expressed in *parts per million* (ppm). The pH value of the AD substrate influences the growth of methanogenic microorganisms and affects the dissociation of some compounds of importance for the AD process (ammonia, sulphide, organic acids). Experience shows that methane formation takes place within a relatively narrow pH interval, from about 5,5 to 8,5 , with an optimum interval between 7,0-8,0 for most methanogens. Acidogenic microorganisms usually have lower value of optimum pH.

The optimum pH interval for mesophilic digestion is between 6,5 and 8,0 and the process is severely inhibited if the pH-value decreases below 6,0 or rises above 8,3. The solubility of carbon dioxide in water decreases at increasing temperature. The pH-value in thermophilic digesters is therefore higher than in mesophilic ones, as dissolved carbon dioxide forms carbonic acid by reaction with water.

The value of pH can be increased by ammonia, produced during degradation of proteins or by the presence of ammonia in the feed stream, while the accumulation of VFA decreases the pH-value.

The value of pH in anaerobic reactors is mainly controlled by the bicarbonate buffer system. Therefore, the pH value inside digesters depends on the partial pressure of CO_2 and on the concentration of alkaline and acid components in the liquid phase. If accumulation of base or acid occurs, the buffer capacity counteracts these changes in pH, up to a certain level. When the buffer capacity of the system is exceeded, drastic changes in pH-values occur, completely inhibiting the AD process. For this reason, the pH-value is not recommended as a stand-alone process monitoring parameter.

The buffer capacity of the AD substrate can vary. Experience from Denmark shows that the buffer capacity of cattle manure varies with the season, possibly influenced by the composition of the cattle feed. The pH-value of domestic animal manure is therefore a variable which is difficult to use for identification of process imbalance, as it changes very little and very slowly. It is, however, important to note that the pH-value can be a quick, relatively reliable and cheap way of registering system imbalance in more weakly buffered systems, such as AD of various wastewater types.

3.3.3 Volatile fatty acids (VFA)

The stability of the AD process is reflected by the concentration of intermediate products like the VFA. The VFA are intermediate compounds (acetate, propionate, butyrate, lactate), produced during acidogenesis, with a carbon chain of up to six atoms. In most cases, AD process instability will lead to accumulation of VFA inside the digester, which can lead furthermore to a drop of pH-value. However, the accumulation of VFA will not always be expressed by a drop of pH value, due to the buffer capacity of the digester, through the biomass types contained in it. Animal manure e.g. has a surplus of alkalinity, which means that the VFA accumulation should exceed a certain level, before this can be detected due to significant decrease of pH value. At such point, the VFA concentration in the digester would be so high, that the AD process will be already severely inhibited.

Practical experience shows that two different digesters can behave totally different in respect to the same VFA concentration, so that one and the same concentration of VFA can be optimal for one digester, but inhibitory for the other one. One of the possible explanations can be the fact that the composition of microorganism populations varies from digester to digester. For this reason, and like in the case of pH, the VFA concentration can not be recommended as a stand-alone process monitoring parameter.

3.3.4 Ammonia

Ammonia (NH_3) is an important compound, with a significant function for the AD process. NH_3 is an important nutrient, serving as a precursor to foodstuffs and fertilizers and is normally encountered as a gas, with the characteristic pungent smell. Proteins are the main source of ammonia for the AD process.

Too high ammonia concentration inside the digester, especially free ammonia (the unionised form of ammonia), is considered to be responsible for process inhibition. This is common to AD of animal slurries, due to their high ammonia concentration, originating from urine. For its inhibitory effect, ammonia concentration should be kept below 80 mg/l. Methanogenic bacteria are especially sensitive to ammonia inhibition. The concentration of free ammonia is direct proportional to temperature, so there is an increased risk of ammonia inhibition of AD processes operated at thermophilic temperatures, compared to mesophilic ones. The free-ammonia concentration is calculated from the equation:

$$[NH_3] = \frac{[T-NH_3]}{\left(1+\frac{H^+}{ka}\right)}$$

where $[NH_3]$ and $[T\text{-}NH_3]$ are the free and respectively the total ammonia concentrations, and *ka* is the dissociation parameter, with values increasing with temperature. This means that increasing pH and increasing temperature will lead to increased inhibition, as these factors will increase the fraction of free ammonia. When a process is inhibited by ammonia, an increase in the concentration of VFA will lead to a decrease in pH. This will partly counteract the effect of ammonia due to a decrease in the free ammonia concentration.

3.3.5 Macro- and micronutrients (trace elements) and toxic compounds

Microelements (trace elements) like iron, nickel, cobalt, selenium, molybdenum or tungsten are equally important for the growth and survival of the AD microorganisms as the macronutrients carbon, nitrogen, phosphor, and sulphur. The optimal ratio of the macronutrients carbon, nitrogen, phosphor, and sulphur (C:N:P:S) is considered 600:15:5:1. Insufficient provision of nutrients and trace elements, as well as too high digestibility of the substrate can cause inhibition and disturbances in the AD process.

Another factor, influencing the activity of anaerobic microorganisms, is the presence of toxic compounds. They can be brought into the AD system together with the feedstock or are generated during the process. The application of threshold values for toxic compounds is difficult, on one hand because these kind of materials are often bound by chemical processes and on the other hand because of the capacity of anaerobic microorganisms to adapt, within some limits, to environmental conditions, herewith to the presence of toxic compounds.

3.4 Operational parameters

3.4.1 Organic load

The construction and operation of a biogas plant is a combination of economical and technical considerations. Obtaining the maximum biogas yield, by complete digestion of the substrate, would require a long retention time of the substrate inside the digester and a correspondingly large digester size. In practice, the choice of system design (digester size and type) or of applicable retention time is always based on a compromise between getting the highest possible biogas yield and having justifiable plant economy. In this respect, the organic load is an important operational parameter, which indicates how much organic dry matter can be fed into the digester, per volume and time unit, according to the equation below:

$$B_R = m * c / V_R$$

B_R	organic load [kg/d*m³]
m	mass of substrate fed per time unit [kg/d]
c	concentration of organic matter [%]
V_R	digester volume [m³]

3.4.2 Hydraulic retention time (HRT)

An important parameter for dimensioning the biogas digester is the hydraulic retention time (HRT). The HRT is the average time interval when the substrate is kept inside the digester tank. HRT is correlated to the digester volume and the volume of substrate fed per time unit, according to the following equation

$$HRT = V_R / V$$

HRT	hydraulic retention time [days]
V_R	digester volume [m³]
V	volume of substrate fed per time unit [m³/d]

According to the above equation, increasing the organic load reduces the HRT. The retention time must be sufficiently long to ensure that the amount of microorganisms removed with the effluent (digestate) is not higher than the amount of reproduced microorganisms. The duplication rate of anaerobic bacteria is usually 10 days or more. A short HRT provides a good substrate flow rate, but a lower gas yield. It is therefore important to adapt the HRT to the specific decomposition rate of the used substrates. Knowing the targeted HRT, the daily feedstock input and the decomposition rate of the substrate, it is possible to calculate the necessary digester volume.

3.4.3 Parameter list

A number of parameters (Table 3.6) can be used for evaluation of biogas plants and for comparing different systems.

In literature two main categories of parameters can be found:

- Operating data, which can be determined by measurement
- Parameters, which can be calculated from the measured data

In order to evaluate the performance capabilities of a biogas plant a multi-criteria analysis should be performed. Evaluations based on a single parameter can never do justice to the process. In order to determine if a biogas plant can provide a return on investment, in an acceptable time frame, economic parameters must always be included.

Table 3.6 Operational parameters of biogas plants

Parameter	Symbol	Unit	Determination
Temperature	T	°C	Measurement during operation
Operational pressure	P	mbar	Measurement during operation
Capacity, throughput	V	m³/d; t/d	Measurement
Reactor volume	V_R	m³	Determined by construction
Gas quantity	V per day V per year	m³/d; m³/a	Measurement during operation and conversion to Nm³
Retention time (hydraulic, minimum guaranteed)	HRT MGRT	d	Calculation from operating data
Organic load		kg oTS / (m³ * d)	Calculation from operating data
Methane concentration in biogas	CH_4	%	Measurement during operation
Specific biogas yield		%	Calculation from operating data
Specific biogas production		m³ / m³	Calculation from operating data
Gross energy		kWh	Determination from the quantity of biogas and methane concentration
Electricity production		kWh	Measurement at the BTTP generator
Output to grid		kWh	Measurement after the BTTP generator
Efficiency of BTTP	η	%	Calculation from operating data
Station supply thermal / electric		kWh	Basis of planning, afterwards measurement during operation
Specific station supply thermal / electric		kWh/m³ Input kWh/GV	Calculation from operating data
Energy production		kWh	Sum of energy that can be sensibly utilized. Calculation from operating data
Plant efficiency	η	%	Net energy drawn from gross energy
Availability		%	Percentage of hours in a year in which a plant is fully functioning
Utilization		%	Ratio of the real quantity input to the projected capacity
Total investment		€	All expenses caused by the biogas plant
Subsidies		€	Pre-determined
Subsidy percentage		%	Percentage of all subsidies in relation to total investments
Specific investments		€/m³ reactor €/GV	Only sensible when primarily manure from animal husbandry is used
Specific treatment costs		€/m³ Input; €/GV	Calculation

4 Main applications of biogas

The production of biogas from AD is widely used by modern society for the treatment of livestock manure and slurries. The aim is to produce renewable energy and to improve their fertiliser quality. In countries with significant agricultural production, the strengthening of environmental legislation and regulation of manure and vegetable wastes recycling increased the interest for AD as a cheap and environmental friendly solution. Latest developments in Europe, USA and other parts of the world have shown increasing interest among farmers to cultivate energy crops, used as feedstock for biogas production. AD is today standard technology for stabilisation of primary and secondary sewage sludge, for treatment of organic industrial waste from food-processing and fermentation industries as well as for the treatment of the organic fraction of municipal solid waste. A special application is biogas recovery from existing landfills.

4.1 Agricultural biogas plants

The agricultural biogas plants are considered those plants which are processing feedstock of agricultural origin. The most common feedstock types for this kind of plants are animal manure and slurries, vegetable residues and vegetable by products, dedicated energy crops (DEC), but also various residues from food and fishing industries etc. Animal manure and slurries, from cattle and pig production, are the basic feedstock for most agricultural biogas plants in Europe, although the number of plants running on DEC was increasing the last years.

AD of animal manure and slurries is considered to improve their fertiliser value for the reasons listed below:

- Manure and slurries from different animals (cattle, pig, poultry etc.) are mixed and co-digested, providing a more balanced content of nutrients
- AD breaks down complex organic material such as organic nitrogen compounds, increasing the amount of plant-available nutrients
- Co-digestion of manure with other substrates adds various amounts of nutrients to the feedstock mixture.

The design and technology of biogas plants differ from country to country, depending on climatic conditions and national frameworks (legislation and energy policies), energy availability and affordability. Based on their relative size, function and location, agricultural AD plants can be classified as:

- Family scale biogas plants (very small scale)
- Farm scale biogas plants (small or medium to large scale)
- Centralised/ joint co-digestion plants (medium to large scale)

4.1.1 Family scale biogas plants

In countries like Nepal, China or India operate millions of family scale biogas plants, utilising very simple technologies. The AD feedstock used in these biogas plants originate from the household and/or their small farming activity and the produced biogas is used for the family cooking and lighting needs.

The digesters are simple, cheap, robust, easy to operate and maintain, and can be constructed with local produced materials. Usually, there are no control instruments and no process heating (psychrophilic or mesophilic operation temperatures), as many of these digesters operate in warmer climates and have long HRT.

a) The Chinese type (Figure 4.1a) is an underground reactor of typically 6 to 8 m³. It is supplied with household sewage, animal manure and organic household waste. The reactor is operated in a semi-continuous mode, where new substrate is added once a day and a similar amount of decanted mixed liquid is removed once a day. The reactor is not stirred, so the sedimentation of suspended solids must be removed 2-3 times per year, occasion when a large portion of the substrate is removed and a small part (about one fifth of the reactor content) is left as inoculum.

b) The Indian type (Figure 4.1b) is similar to the Chinese type as it is a simple underground reactor for domestic and small farming waste. The difference is that the effluent is collected at the bottom of the reactor and a floating gas bell functions as a biogas reservoir.

c) Another small scale biogas plant is the displacement type, which consists of a horizontal cylindrical reactor. The substrate is fed at one end and the digestate is collected at the opposite end. The substrate moves through the reactor as a plug flow, and a fraction of the outlet is re-circulated to dilute the new input and to provide inoculation.

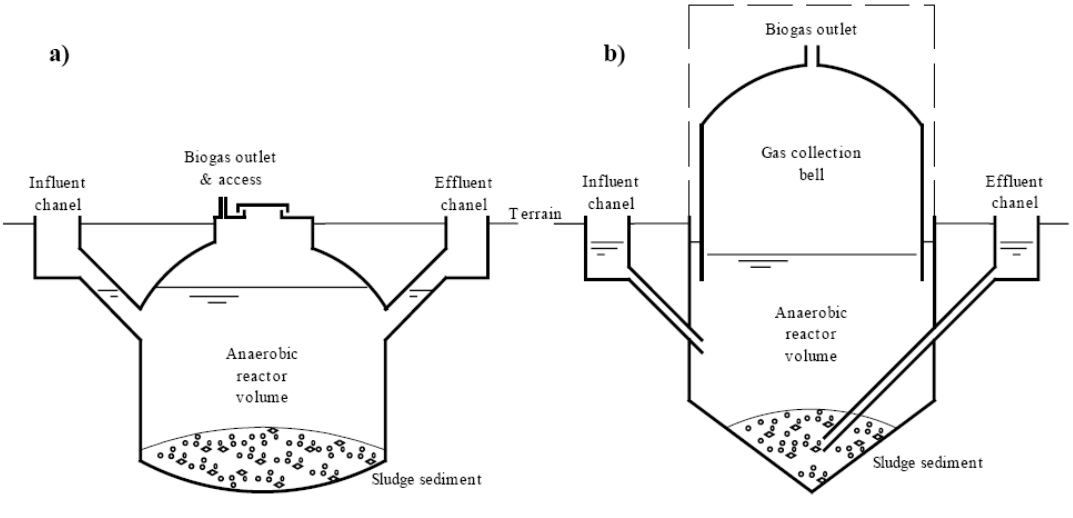

Figure 4.1 Principles of rural biogas reactor types: a) Chinese type; b) Indian type (ANGELIDAKI 2004)

4.1.2 Farm-scale biogas plants

A farm scale biogas plants is named the plant attached to only one farm, digesting the feedstock produced on that farm. Many farm scale plants co-digest also small amounts of methane rich substrates (e.g. oily wastes from fish industries or vegetable oil residues), aiming to increase the biogas yield. It is also possible that a farm scale biogas plant receives and processes animal slurries from one or two neighbouring farms (e.g. via pipelines, connecting those farms to the respective AD unit).

There are many types and concepts of farm scale biogas plants around the world. In Europe, countries like Germany, Austria and Denmark are among the pioneers of farm scale biogas production. The interest of European farmers in AD applications is growing nowadays, not only because agricultural biogas production transforms waste products into valuable resources and produces high quality fertiliser but also because it creates new business opportunities for the involved farmers and gives them a new status, as renewable energy providers.

The farm scale biogas plants have various sizes, designs and technologies. Some are very small and technologically simple, while others are rather large and complex, similar to the centralised co-digestion plants (see Chapter 4.1.3). Nevertheless, they all have a common principle layout: manure is collected in a pre-storage tank, close to the digester and pumped into the digester, which is a gas-tight tank, made of steel or concrete, insulated to maintain a constant process temperature. Digesters can be horizontal (Figure 4.2 and 4.3) or vertical, usually with stirring systems, responsible for mixing and homogenising the substrate, and minimising risks of swimming-layers and sediment formation. The average HRT is commonly of 20 to 40 days, depending on the type of substrate and digestion temperature.

Digestate is used as fertiliser on the farm and the surplus is sold to plant farms in the nearby area. The produced biogas is used in a gas engine, for electricity and heat production. About 10 to 30% of the produced heat and electricity is used to operate the biogas plant and for domestic needs of the farmer, while the surplus is sold to power companies and respectively to neighbouring heat consumers.

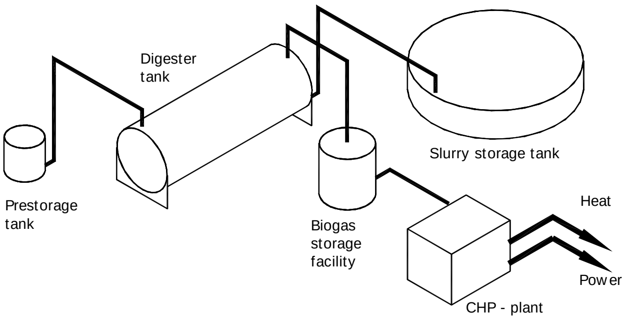

Figure 4.2 Schematic representation of a farm scale biogas plant, with horizontal digester of steel. (HJORT-GREGERSEN 1998)

Apart from the digester, equipped with stirring system, the plant can include pre-storage for fresh biomass, storage for digested biomass and for biogas, and even a CHP unit.

Figure 4.3 Horizontal digester, built in Denmark (Nordisk Folkecenter 2001)

The digester can also be vertical, with or without conic bottom (Figure 4.4 and 4.5), a so-called 'two-in-one' slurry storage and digester tank, where the digester is build inside the storage tank for digestate. The two tanks are covered with a gas tight membrane, inflated by the emerging gas production and stirred by electric propeller. The plant can furthermore consist of a pre-storage tank for the co-substrate and a CHP-unit.

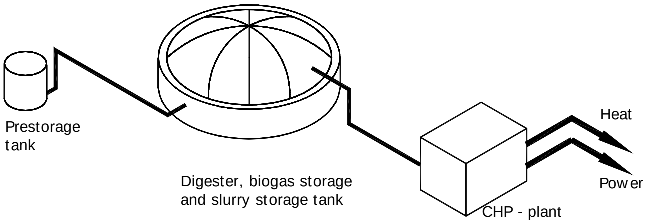

Figure 4.4 Schematic representation of the 'two–in-one' farm scale plant, with soft membrane cover (HJORT-GREGERSEN 1998)

Figure 4.5 Picture of farm scale biogas plant in Denmark, co-digesting animal slurries and energy crops (GROENGAS A/S)

Figure 4.6 Vertical digester in Germany, processing pig and poultry manure and crop silage (KRIEG AND FISHER 2008)

A recent development of the farm scale biogas plant is the concept of energy-crop based plants. Their advantage is that the energy content of energy crops is much higher than of most of the organic waste materials. The major limitations of these kinds of biogas plants are related to operation costs, land use and availability.

Figure 4.7 Vertical digester in Germany, built in 2005 for digestion of energy crops (KRIEG and FISHER 2008)

4.1.3 Centralised (joint) co-digestion plants

Centralised co-digestion is a concept based on digesting animal manure and slurries, collected from several farms, in a biogas plant centrally located in the manure collection area. The central location of the biogas plant aims to reduce costs, time and manpower for the transport of biomass to and from the biogas plant. Centralised AD plants co-digest animal manure with a variety of other suitable co-substrates (e.g. digestible residues from agriculture, food- and fish industries, separately collected organic household wastes, sewage sludge). The centralised co-digestion plants (also named joint co-digestion plants) were developed and are largely applied in Denmark (Figure 4.8), but also in other regions of the world, with intensive animal farming.

Animal manure and slurries are collected from the pre-storage tanks or from the slurry channels at the farm and transported in special vacuum container trucks to the biogas plant, according to an established schedule. At the biogas plant, manure is mixed with the other co-substrates, homogenised and pumped inside the digester tank. The transport of fresh manure from the farmers to the biogas plant and of digestate from the biogas plant to the farmer's storage facilities, placed close to the fields where digestate is applied as fertiliser, is the responsibility of the biogas plant. The storage facilities for digestate are sometimes shared by several farmers.

Like in the case of farm plants, the digestion process can be mesophilic or thermophilic. The HRT is of 12-25 days. According to European legislation, a controlled sanitation process of certain types of substrates of animal origin must be performed prior accessing the digester, which provides effective reduction of pathogens and weed seeds and ensures safe recycling of digestate.

Figure 4.8 Picture of centralised co-digestion plant in Denmark (LEMVIG BIOGAS)

The digester feeding system is continuous, and biomass mixture is pumped in and out of the digesters in equal amounts through precise pump-sequences. Digestate, pumped out of the digester, is transferred by pipelines to temporary storage tanks. In many cases, these tanks are covered with a gas proof membrane, for the collection of the additional biogas production (up to 15% of the total), taking place at lower temperature. Before leaving the biogas plant, digestate is analysed and nutritionally defined (DM, VS, N, P, K, and pH). The manure suppliers can take back only that amount of digestate, which they are allowed by law to spread on their fields. The excess is sold as fertiliser to the crop farmers in the nearby area. In all cases, digestate is integrated in the fertilisation plan of the farm, replacing mineral fertilisers, closing the cycle of carbon and nutrient recycling (Figure 4.9). More and more biogas plants are also equipped with installations for separation of digestate in liquid and solid fractions.

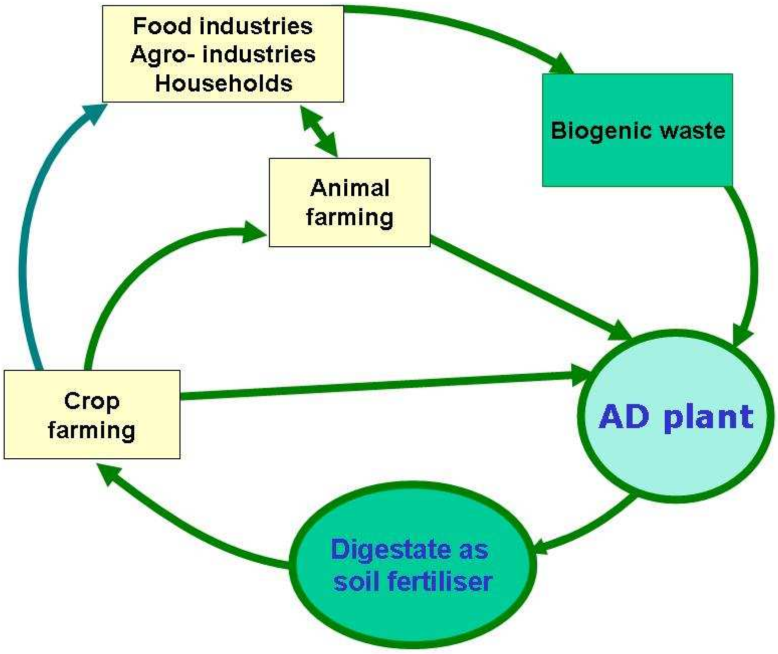

Figure 4.9 Schematic representation of the closed cycle of centralised AD (AL SEADI 2001)

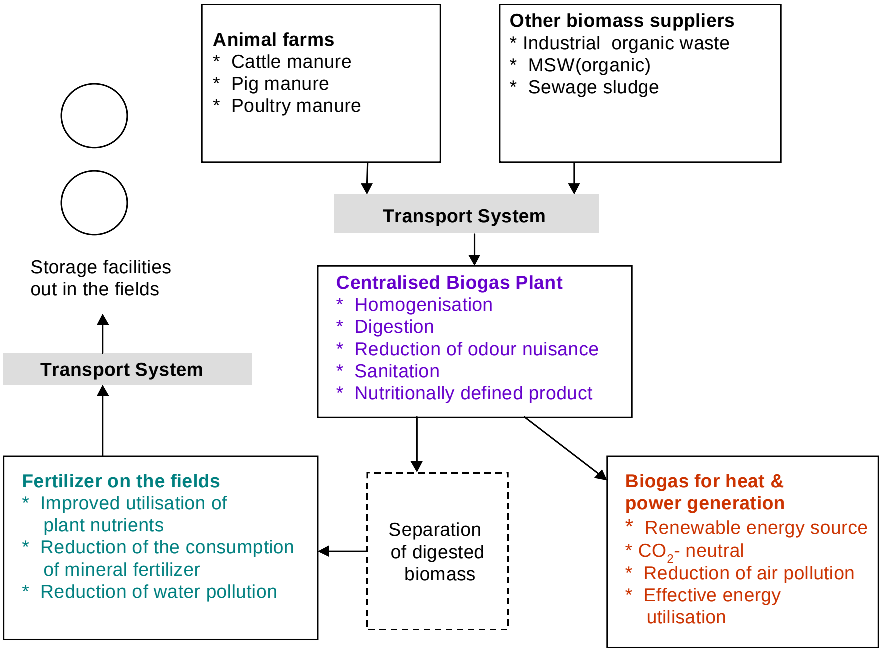

Figure 4.10 The integrated concept of centralised co-digestion plant

This way, centralised co-digestion represents an integrated system of renewable energy production, organic waste treatment and nutrient recycling. Experience shows that the system (Figure 4.10) is capable to generate agricultural, environmental and economic benefits for the farmers involved and for the overall society such as:

- Renewable energy production
- Cheap and environmentally safe recycling of manure and organic wastes
- Reduction of greenhouse gas emission
- Improved veterinary safety through sanitation of digestate
- Improved fertilisation efficiency
- Less nuisance from odours and flies
- Economical benefits for the farmers

Centralised co-digestion plants can be organised as co-operative companies, with farmers supplying manure an energy consumers as shareholders and owners. The management of the biogas plant is undertaken by a board of directors, which also employs the necessary personnel and is responsible for economic and legal binding agreements concerning the construction of the plant, the feedstock supply, the distribution and sale of digestate, the sale of biogas or/and energy and the financing activities. The co-operative company proved to be a functional organisational structure, economically feasible in countries like Denmark, but other organisation forms like Ltd. companies or municipally owned companies are also frequent.

4.2 Waste water treatment plants

AD is largely used for treatment of primary and secondary sludge, resulted from aerobic treatment of municipal waste water. The system is applied in many countries in combination with advanced treatment systems where the AD process is used to stabilise and reduce the final amount of sludge. Most engineering companies providing sewage treatment systems have also the capability to provide AD systems. In European countries, between 30 and 70% of sewage sludge is treated by AD, depending on national legislation and priorities.

The AD treated sludge effluent can be further used as fertiliser on agricultural land or for energy production by incineration. There are still countries where the effluent is disposed on landfill sites. As this practice can have negative consequences for the environment due leakage of nutrients to ground water and emissions of GHG to the atmosphere, it is therefore banned in most European countries.

Figure 4.11 Waste water treatment plant in Psyttalia, Greece (FARNSWORTH 2004)

4.3 Municipal solid waste (MSW) treatment plants

In many countries, municipal solid waste is collected as mixed stream and incinerated in large power plants or disposed on landfill sites. This practice is actually a waste of energy and nutrients, as most of the organic fraction could be source separated and used as AD feedstock. Even bulk collected wastes can be further processed and used for biogas production.

In recent years, source separation and recycling of wastes received increasing attention. As a result, separate fractions of MSW are now becoming available for more advanced recycling treatment, prior to disposal. The origin of the organic waste is important in determining which treatment method is most appropriate. Kitchen waste is generally too wet and lacks in structure for aerobic composting, but provides an excellent feedstock for AD. On the other hand, woody wastes contain high proportions of lignocellulosic material are better suited for composting, as pre-treatment is necessary in order to be used for AD.

Utilisation of source separated organic fraction of household waste for biogas production has a large potential and several hundred AD plants, processing organic fraction of MSW, are in operation around the world. The aim is to reduce the stream of organic wastes to landfills or even to incineration and to redirect them towards recycling.

4.4 Industrial biogas plants

Anaerobic processes are largely used for the treatment of industrial wastes and waste waters for more than a century and AD is today a standard technology for the treatment of various industrial waste waters from food-processing, agro-industries, and pharmaceutical industries. AD is also applied to pre-treat organic loaded industrial waste waters, before final disposal. Due to recent improvements of treatment technologies, diluted industrial waste waters can also be digested. Europe has a leading position in the world regarding this application of AD. In recent years energy considerations and environmental concerns have further increased the interest in direct anaerobic treatment of organic industrial wastes and the management of organic solid wastes from industry is increasingly controlled by environmental legislations. Industries using AD for wastewater treatment range from:

- Food processes: e.g. vegetable canning, milk and cheese manufacture, slaughterhouses, potato processing industry
- Beverage industry: e.g. breweries, soft drinks, distilleries, coffee, fruit juices
- Industrial products: e.g. paper and board, rubber, chemicals, starch, pharmaceuticals

Industrial biogas plants bring about a number of benefits for the society and the industries involved:

- Added value through nutrient recycling and cost reductions for disposal
- Utilisation of biogas to generate process energy
- Improved environmental image of the industries concerned, through environmental friendly treatment of the produced wastes

It is expected that the environmental and socio-economic benefits of AD, complemented by higher costs/taxation of other disposal methods, will increase the number of applications of industrial biogas in the future.

4.5 Landfill gas recovery plants

Landfills can be considered as large anaerobic plants with the difference that the decomposition process is discontinuous and depends on the age of the landfill site. Landfill gas has a composition which is similar to biogas, but it can contain toxic gases, originating from decomposition of waste materials on the site.

Recovery of landfill gas is not only essential for environmental protection and reduction of emissions of methane and other landfill gases (Figure 4.12), but it is also a cheap source of energy, generating benefits through faster stabilisation of the landfill site and revenues from the gas utilisation. Due to the remoteness of landfill sites, landfill gas is normally used for electricity generation, but the full range of gas utilisation, from space heating to upgrading to vehicle fuel and pipeline quality is possible as well (Figure 4.13 and 4.14).

Landfill gas recovery can be optimised through the management of the site such as shredding the waste, re-circulating the organic fraction and treating the landfill as a bioreactor. A landfill bioreactor is a controlled landfill, designed to accelerate the conversion of solid waste into methane and is typically divided into cells, provided with a system to collect leachate from the base of the cell. The collected leachate is pumped up to the surface and redistributed across the waste cells, transforming the landfill into a large high-solids digester.

Figure 4.12 Gaseous emissions and leaching to ground water from landfill sites are serious threats for the environment

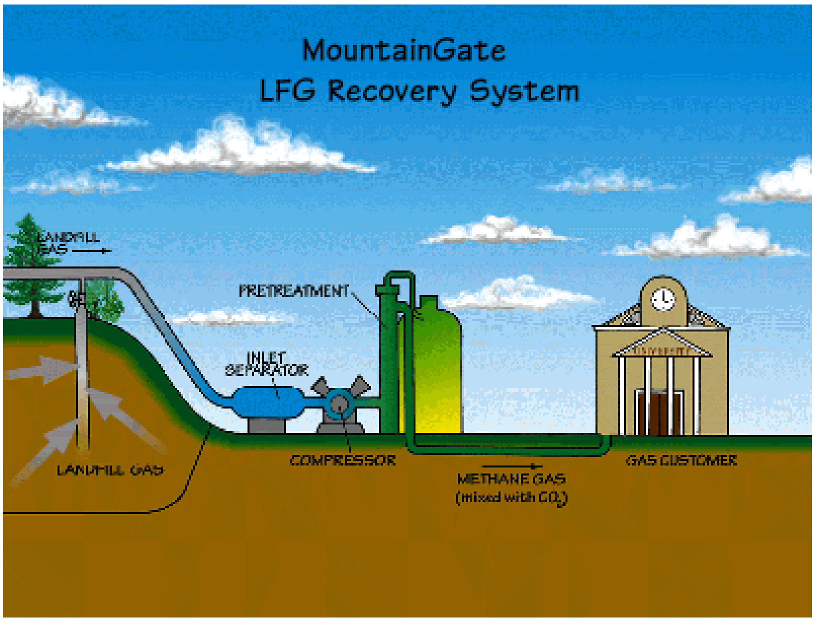

Figure 4.13 Landfill gas recovery system (NST ENGINEERS 2007)

Figure 4.14 Ano Liosia Landfill gas exploitation project, Athens, Greece

5 Utilisation of biogas

Biogas has many energy utilisations, depending on the nature of the biogas source and the local demand. Generally, biogas can be used for heat production by direct combustion, electricity production by fuel cells or micro-turbines, CHP generation or as vehicle fuel (Figure 5.1.).

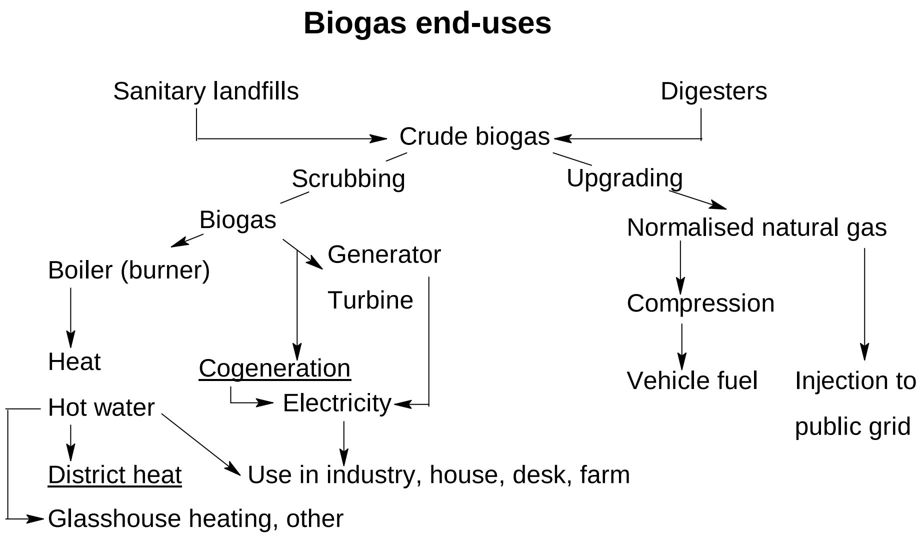

Figure 5.1 Overview of biogas utilisation

5.1 Biogas properties

The energy content of biogas from AD is chemically bounded in methane. The composition and properties of biogas varies to some degree depending on feedstock types, digestion systems, temperature, retention time etc. Table 5.1 contains some average biogas composition values, found in most of the literature. Considering biogas with the standard methane content of 50%, the heating value is of 21 MJ/Nm³, the density is of 1,22 kg/Nm³ and the mass is similar to air (1.29 kg/Nm³).

Table 5.1 Composition of biogas

Compound	Chemical symbol	Content (Vol.-%)
Methane	CH_4	50-75
Carbon dioxide	CO_2	25-45
Water vapour	H_2O	2 (20°C) -7 (40°C)
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Hydrogen sulphide	H_2S	<1

The biochemical composition of different feedstock types varies is determinant for their theoretical methane yield, as seen in Table 5.2.

Table 5.2 Theoretical gas yields

Substrate	Litre Gas / kg TS	CH_4 [%]	CO_2 [%]
Raw protein	700	70 to 71	29 to 30
Raw fat	1 200 to 1 250	67 to 68	32 to 33
Carbohydrates	790 to 800	50	50

The methane yield of the AD substrates depends on the content of proteins, fats, and carbohydrates, as shown in Table 5.3.

Table 5.3 Methane yields of different feedstock material

Feedstock	Methane yield [%]	Biogas yield [m³/tFF*]
Liquid cattle manure	60	25
Liquid pig manure	65	28
Distillers grains with solubles	61	40
Cattle manure	60	45
Pig manure	60	60
Poultry manure	60	80
Beet	53	88
Organic waste	61	100
Sweet sorghum	54	108
Forage beet	51	111
Grass silage	54	172
Corn silage	52	202

** FF=fresh feedstock*

5.2 Direct combustion and heat utilisation

The simplest way of utilising biogas is direct burning in boilers or burners, extensively used for the biogas produced by small family digesters. Direct combustion, in natural gas burners, is applied in many countries as well. Biogas can be burned for heat production either on site, or transported by pipeline to the end users. For heating purposes biogas does not need any upgrading, and the contamination level does not restrict the gas utilisation as much as in the case of other applications. However, biogas needs to undergo condensation and particulate removal, compression, cooling and drying.

5.3 Combined heat and power (CHP) generation

CHP generation is a standard utilisation of biogas from AD in many countries with a developed biogas sector, as it is considered a very efficient utilisation of biogas for energy production. Before CHP conversion, biogas is drained and dried. Most gas engines have maximum limits for the content of hydrogen sulphide, halogenated hydrocarbons and siloxanes in biogas. An engine based CHP power plant has an efficiency of up to 90% and produces 35% electricity and 65% heat.

The most common types of CHP plants are block type thermal power plants (BTTP) with combustion motors that are coupled to a generator. Generators usually have a constant rotation of 1500 rpm (rotations per minute) in order to be compatible with the grid frequency. Motors can be Gas-Otto, Gas-Diesel or Gas-Pilot Injection engines. Both, Gas-diesel and Gas-Otto engines are operating without ignition oil, according to the Otto principle. The difference between these engines is only the compression. Thus, both motors will be referred to as Gas-Otto motors in the rest of the text. Alternatives to the above mentioned BTTPs are micro gas turbines, Stirling motors and fuel cells, all of them technologies undergoing important developmental steps during the recent years and described in more details in the following chapters.

Figure 5.2 Biogas burner for heat production (AGRINZ 2008)

The produced electricity from biogas can be used as process energy for electrical equipment such as pumps, control systems and stirrers. In many countries with high feed-in tariffs for renewable electricity, all the produced electricity is sold to the grid and the process electricity is bought from the same national electricity grid.

An important issue for the energy and economic efficiency of a biogas plant is the utilisation of the produced heat. Usually, a part of the heat is used for heating the digesters (process heating) and approximately $^2/_3$ of all produced energy can be used for external needs. Many of the early generations of biogas plants have being established exclusively for electricity purposes, without consideration for the utilisation of the produced heat. Nowadays, the heat utilisation is considered a very important aspect for the economy of the plant. For many biogas plants, the sale of electricity alone is not enough for being economically sustainable which is why the new established biogas plants should include heat utilisation in the overall plant design.

Biogas heat can be used by industry processes, agricultural activities or for space heating. The most suitable heat user is the industry, as the demand is constant throughout the whole year. Heat quality (temperature) is an important issue for industrial applications. The use of heat from biogas for building and household heating (mini-grid or district heating) is another option, although this application has a low season during summer and a high season during winter. Biogas heat can also be used for drying crops, wood chips or for separation and further treatment of digestate. Finally, heat can be used in ’power-heat-cooling-coupling’-systems. This process, known from refrigerators, is used e.g. for cooling food storage or for air conditioning. The input energy is heat, which is converted into cooling through a sorption process, whereby a differentiation is made between adsorption and absorption cooling process. The advantage of cooling by sorption is the low wear, due to few mechanical parts, and the low energy consumption, compared to compression cooling plants. The use of power-heat-cooling-coupling in biogas plants is currently being tested through several pilot projects.

5.3.1 Gas-Otto engines

Gas-Otto motors are developed specifically for using biogas according to the Otto principle. The engines (lean burn engines) are operated with air surplus, in order to minimise carbon monoxide emissions. This leads to lower gas consumption and reduced motor performance, compensated by using an exhaust turbo charger. Gas-Otto motors require biogas with minimum 45% methane content. Smaller engines, up to 100 kW_{el} are usually Otto engines. For higher electrical performance, adapted diesel aggregates are used. They are equipped with spark plugs. Both engines are named ‘Gas-Otto Engines’ since their basic operation is based on the Otto principle. Gas-Otto engines (Figure 5.3) can be operated with biogas or natural gas. This is useful during the start-up of the biogas plant when the heat is used for heating up digesters.

Figure 5.3 Gas-Otto engines (RUTZ 2007)

5.3.2 Pilot-injection gas motor

The Pilot Injection Engine (also called Pilot Injection Natural Gas Engine, PING, or Dual Fuel Engine) is based on the diesel engine principle. These engines are often used for tractors and heavy duty vehicles. The biogas is mixed in a gas mixer, together with the combustion air. This mixture passes through an injection system in the combustion chamber where it is ignited by the injected ignition oil. Usually up to 10% ignition oil is automatically injected and combusted. Pilot injection engines are operated with high air surplus.

In case of disrupted biogas supply, pilot injection motors can also operate with pure ignition oil or diesel, without any problem. The replacement of biogas by oil or diesel can be necessary during the start up phase of the biogas plant for process heat production. The ignition oil can be fossil diesel or heating oil, but renewable rapeseed-methyl-ester (biodiesel) or vegetable oil can be used in the same way. The advantage of renewable ignition oils is that they are sulphur-free and emit less carbon monoxide. Furthermore, they are biodegradable which is important in case of leaching and spilling. However, if biofuels are used, higher filter wear, jet clogging and lower viscosity of the vegetable oil must be taken into consideration. Another disadvantage is the release of nitrous oxide. In any case, it is important to follow the fuel quality instructions of the engine manufacturers.

5.3.3 Stirling motors

The Stirling motor operates without internal combustion, based on the principle that temperature changes of gases result in volume changes. The pistons of the engine are moved by gas expansion caused by heat injection from an external energy source. The necessary heat can be provided from various sources such as a gas burner, running on biogas. In order to use Stirling engines for biogas some technical adaption is necessary. Due to external combustion, also biogas with lower methane content can be used.

The electrical efficiency of the Stirling engine is of 24-28%, which is lower than Gas-Otto engines. The exhaust temperatures are between 250-300°C. The capacity of Stirling motors is usually below 50 kW_{el}. Due to the low wear of components, low maintenance costs can be expected. The Stirling engine can be used in block type thermal power plants.

5.4 Biogas micro-turbines

In biogas micro-turbines, air is pressed into a combustion chamber at high pressure and mixed with biogas. The air-biogas mixture is burned causing the temperature increase and the expanding of the gas mixture. The hot gases are released through a turbine, which is connected to the electricity generator (Figure 5.4). The electric capacity of micro-turbines is typically below 200 kW_e. The cost of biogas micro-turbines is high and the research and development work in this area is therefore aiming cost reduction for future models.

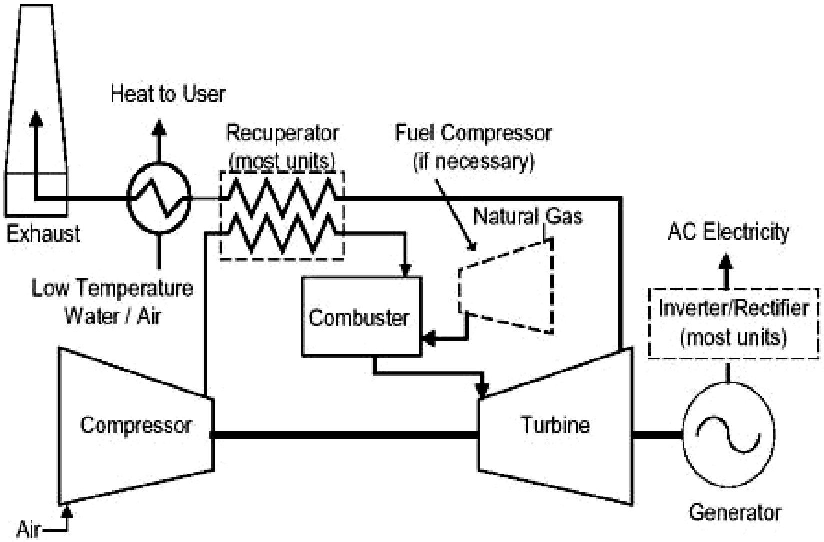

Figure 5.4 Micro-turbine structure (www.energysolutionscenter.org)

5.5 Fuel cells

The fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. The basic physical structure (building block) of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on both sides (Figure 5.5). In a typical fuel cell, the gaseous fuel (biogas) is fed continuously to the anode (the negative electrode) compartment and an oxidant (i.e. oxygen from air) is fed continuously to the cathode (the positive electrode) compartment. An electrochemical reaction takes place at the electrodes, producing electric current.

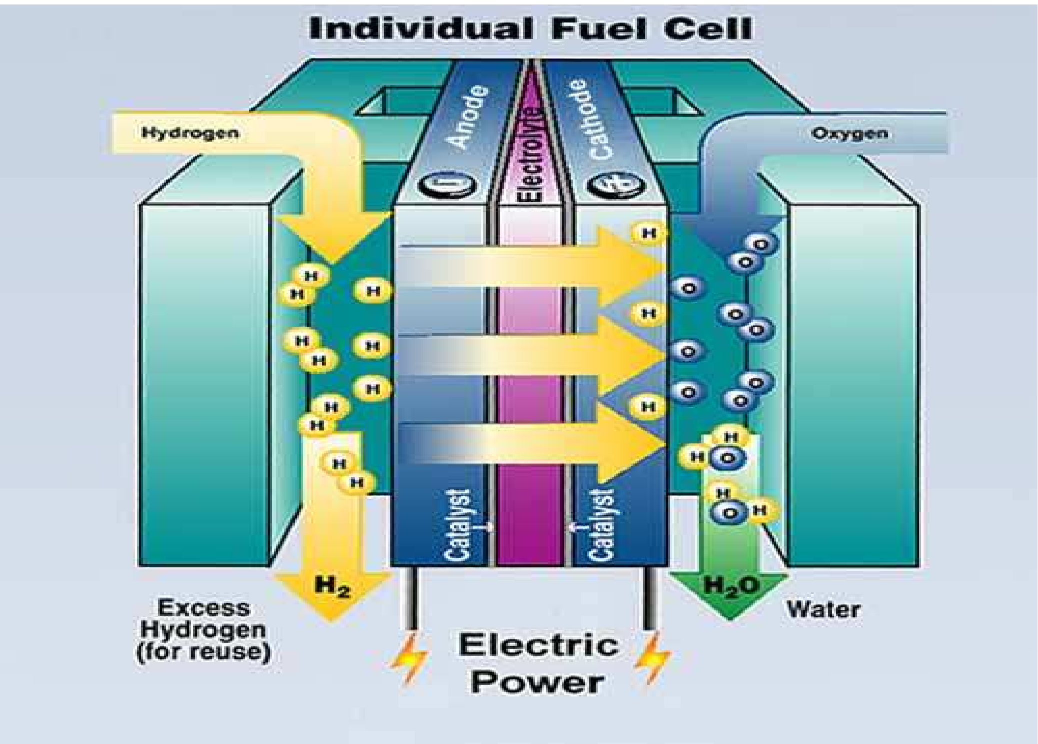

Figure 5.5 Simplified scheme of a fuel cell (EMERGING ENVIRONMENTAL ISSUES 2005)

There are various fuel cell types suitable for biogas, named according to the type of electrolyte used. They can be low (AFC, PEM), medium (PAFC) or high temperature fuel cells (MCFC, SOFC). The choice of the fuel cell type depends on the gaseous fuel used and the heat utilisation.

PEM -*The Polymer-Electrolyte-Membrane* fuel cell can be used for biogas. Due to operating temperature of 80°C, the heat can be fed directly into a heat/warm water network. The type of electrolyte used influence the service life of PEM, which is very sensitive to impurities in the fuel gas, including carbon dioxide. For this reason, gas cleaning is very important.

PAFC - *Phosphoric Acid Fuel Cell*, frequently used with natural gas worldwide. Compared to other fuel cells, the electrical efficiency is low but the advantage is that PAFC is less sensitive to the presence of carbon dioxide and carbon monoxide in the gas.

MCFC - *Molten Carbonate Fuel Cell* is uses a fluid carbon flow as electrolyte. MCFC is insensitive to carbon monoxide and tolerates carbon dioxide concentrations up to 40% of volume content. Due to its operation temperature of 600 -700°C, conversion of methane into hydrogen, also called reforming, can take place inside the cell. Its dissipated heat can for example be used in a downstream turbine.

SOFC - *Solid Oxide Fuel Cell* is another type of high-temperature fuel cell, operating at 750-1 000°C. The SOFC fuel cell has a high electrical efficiency and the reforming of methane to hydrogen can take place within the cell. The use of biogas is suited due to its low sensitivity to sulphur.

Figure 5.6 World's first MCFC fuel cell for biogas, operating in Germany (RUTZ 2007)

The investment costs of all biogas fuel cells are much higher than for engine driven BTTPs, amounting some 12 000 €/kW. As in the case of biogas micro-turbines, the research and development work in this area is targeting competitive costs for the future models.

5.6 Biogas upgrading (Biomethane production)

Biogas can be distributed through the existing natural gas networks and used for the same purposes as natural gas or it can be compressed and used as renewable vehicle fuel. Prior to injection into the natural gas grid or to utilisation as vehicle fuel, biogas must undergo an upgrading process, where all contaminants as well as carbon dioxide are removed and the content of methane must is increased from the usual 50-75% to more than 95%. The upgraded biogas is often named biomethane.

Various technologies can be applied for removal of contaminants and for increasing the methane content of biogas.

Removal of carbon dioxide is done in order to reach the required Wobbe index of gas. When removing carbon dioxide from biogas, small amounts of methane CH_4) are also removed. As methane has a 23-fold stronger greenhouse gas effect than CO_2, (i.e. a molecule of methane is 23 times more effective than a molecule of CO_2 in trapping the radiated heat from earth) it is important to keep methane losses low, for both economic and environmental reasons. Two common methods of removing carbon dioxide from biogas are absorption (water scrubbing, organic solvent scrubbing) and adsorption (pressure swing adsorption, PSA). Less frequently used are membrane separation, cryogenic separation and process internal upgrading, which is a relatively new method, currently under development.

Figure 5.7 Biogas upgrading installation (*left*) and the connection point to the natural gas grid (*right*) of the biomethane plant in Pliening, Germany (RUTZ 2007)

The total cost for cleaning and upgrading biogas consists of investment costs and of operation and maintenance costs. In the case of investment costs, an important factor is the size of the plant. The total investment costs increase with increased plant capacity but investment per unit of installed capacity is lower for larger plants, compared to small ones. In the case of operation costs, the most expensive part of the treatment is the removal of carbon dioxide.

5.6.1 Biogas as vehicle fuel

Utilisation of biogas in the transport sector is a technology with great potential and with important socio-economic benefits. Biogas is already used as vehicle fuel in countries like Sweden, Germany and Switzerland.

The number of private cars, public transportation vehicles and trucks driven on biogas (biomethane) is increasing. Biomethane can be used as fuel in the same way and by the same vehicles like the natural gas. An increasing number of European cities are exchanging their diesel buses with biomethane driven ones.

Many biogas driven private cars are converted vehicles, which have been retro-fitted with a compressed gas tank, in the luggage compartment, and a gas supply system, in addition to the fossil fuel system.

There are also specially built biogas vehicles, which are optimised for better efficiency and more convenient placement of gas cylinders, without losing luggage space. The biogas is stored at 200 to 250 bars, in pressure vessels, made of steel or aluminium composite materials. Today, more than 50 manufacturers worldwide offer some 250 models of commuter, light and heavy duty gas driven vehicles.

Heavy duty vehicles can be converted to run on methane gas only, but in some cases also dual fuel engines are used. A dual fuel engine uses a diesel injection system and the gas is ignited by injection of a small amount of diesel oil. Dual fuel engines require less engine development and maintain the same driveability as a diesel vehicle. However, emission values are not as low as for the corresponding specially built gas vehicles and the engine technology remains a compromise between spark ignition and diesel engine.

Biomethane vehicles have substantial overall advantages compared to vehicles equipped with petrol or diesel engines. The overall carbon dioxide emissions are drastically reduced, depending on the feedstock substrate and origin of electricity (fossil or renewable) used for gas upgrading and compressing. Emission of particles and soot are also drastically reduced, even compared with very modern diesel engines, equipped with particle filters. Emissions of NO_x and *Non Methane Hydrocarbons* (NMHC) are also drastically reduced.

Upgraded biogas (biomethane) is considered to have the highest potential as vehicle fuel, even when compared to other biofuels. Figure 5.8 shows a comparison between transport biofuels, in terms of covered distance by an automobile, when running on the respective biofuel, produced on energy crops cultivated on one hectare arable land. The potential of biogas for the transport sector is even higher, if waste is used as feedstock, instead of energy crops.

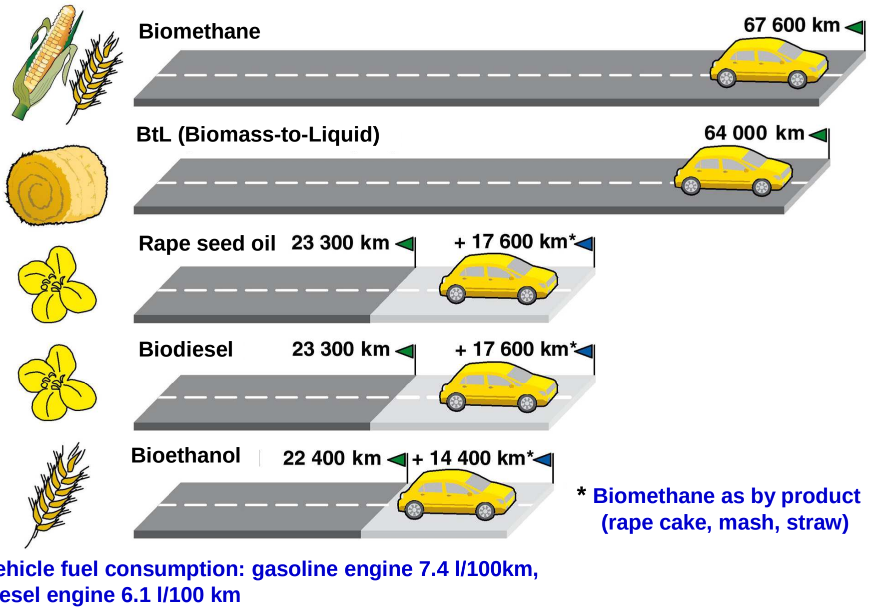

Figure 5.8 Biofuels in comparison: Range of a personal car, running on biofuels produced on feedstock/energy crops from one hectare arable land. Source (FNR 2008)

5.6.2 Biomethane for grid injection

Upgraded biogas (biomethane) can be injected and distributed through the natural gas grid, after it has been compressed to the pipeline pressure. In many EU countries, the access to the gas grid is guaranteed for all biogas suppliers.

There are several advantages of using the gas grid for distribution of biomethane. One important advantage is that the grid connects the production site of biomethane, which is usually in rural areas, with more densely populated areas. This enables the gas to reach new customers. It is also possible to increase the biogas production at a remote site, without concerns about utilisation of heat excess. Grid injection means that the biogas plant only needs a small CHP unit for the process energy or a biogas burner.

Countries like Sweden, Switzerland, Germany and France have standards (certification systems) for injecting biogas into the natural gas grid. The standards, prescribing the limits for components like sulphur, oxygen, particles and water dew point, have the aim of avoiding contamination of the gas grid or the end users. The Wobbe index was introduced, to avoid influence on gas measurements and end use. The standards are in most cases easily achievable through current upgrading processes. For this kind of application, landfill gas can be difficult to upgrade to acceptable quality due to its high nitrogen content.

In Europe, biogas feed plants are in operation in Sweden, Germany, Austria, the Netherlands, Switzerland and France. The main barriers for biomethane injection are the high costs of upgrading and grid connection. Grid injection is also limited by location of suitable biomethane production and upgrading sites, which have to be close to the natural gas grid.

5.6.3 Carbon dioxide and methane production as chemical products

Production of pure methane and CO_2 from biogas can be a viable alternative to methane and carbon dioxide production from fossil sources. Both substances are important for the chemical industry. Pure CO_2 is used for production of polycarbonates, of dry ice or for surface treatment (sandblasting with CO_2). CO_2 from biogas can also be used in agriculture, as fertiliser in greenhouses.

6 Utilisation of digestate

Agricultural biogas production is an integrated element of modern, holistic agriculture, which takes into consideration not only economic costs and benefits of agricultural activities, but also socio-economic and environmental benefits. Agricultural biogas production provides intertwined agricultural, economic and environmental benefits and for this reason, the promoters of the biogas development in Europe, after the oil crisis, were the organic farmers, interested in AD not only for renewable energy generation, but as a way to improve fertiliser quality of their animal manure.

6.1 AD - a technology for animal manure and slurry management in intensive areas

Animal production is known also for producing large amounts of animal manure. There are frequent situations where the animal farms do not own enough agricultural land for using optimally the produced manure and slurries as fertiliser. The excess of animal manure requires adequate manure management measures, to prevent serious consequences of excessive fertilisation with animal manure in these areas, such as:

- Pollution of ground and surface water through leakage
- Damage of soil structure and soil microbiology
- Damage of specific grassland vegetation populations and formation of typical “slurry vegetation”
- Increased risks of methane and ammonia emissions
- Odour and fly nuisance, from manure storage and application
- Increased risk of contamination and of spreading pathogens

AD of animal manure and slurries can be the solution to the above situation, allowing environmental friendly agricultural practices.

6.2 From raw slurry to digestate as fertiliser

6.2.1 Biodegradation of organic matter

Treatment of animal manure and slurries in biogas plants results in biodegradation of organic matter to inorganic compounds and methane. In practice, the anaerobic degradation rate of organic matter from animal manure and slurries is about 40% for cattle slurry and of 65% for pig slurry. The degradation rate depends at large on feedstock type (Table 6.1), HRT and process temperature. Due to degradation of organic matter, digestate is easier to pump and easier to apply as fertiliser, with reduced need of stirring, compared to untreated slurry.

Table 6.1 Nutrient distribution in digestate, compared to cattle and pig slurry

	Dry matter %	**Total N kg/ton**	**NH_4-N kg/ton**	**P kg/ton**	**K kg/ton**	**pH**
Cattle slurry	6,0	5,0	2,8	0,8	3,5	6,5
Pig slurry	4,0	5,0	3,8	1,0	2,0	7,0
Digested slurry	2,8	5,0	4,0	0,9	2,8	7,5

6.2.2 Reduction of odours

One of the noticeable positive changes which take place through AD of manure is the significant reduction of odoriferous substances (volatile acids, phenol and phenol derivatives).

Experience shows that up to 80% of odours in feedstock substrates can be reduced by AD. It is not only a reduction of the intensity and persistence of odours (Figure 6.1), but also a positive change in the composition of odours, as digestate no longer has the unpleasant slurry smell, but smells more like ammonia. Even if stored for longer periods of time, digestate shows no increase in emission of odours. Figure 6.1 shows that, 12 hours after the application of digestate, the odour has almost disappeared.

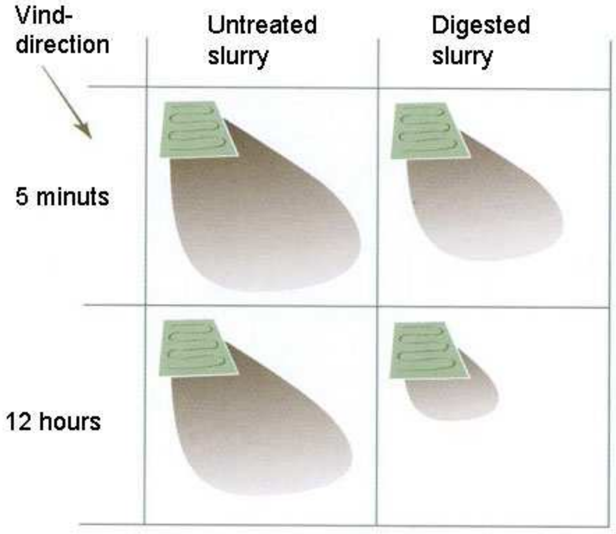

Figure 6.1 Area affected and persistence of odour nuisance, after application of digestate and of untreated slurry, on a field with northwest wind (BIRKMOSE 2002)

6.2.3 Sanitation

The AD process is able to inactivate viruses, bacteria and parasites in the treated feedstock substrates, an effect which is usually called sanitation. The sanitation efficiency of AD depends on the actual retention time of the feedstock inside the digester, the process temperature, the stirring technique and digester type. The best sanitation is obtained at thermophilic temperatures (50-55°C) in e.g. an elongated plug flow reactor, with the appropriate retention time. In this digester type no mixing of digestate with fresh feedstock occurs, allowing up to 99% of all pathogens to be destroyed.

In order to ensure veterinary safe recycling of digestate as fertiliser, European legislation requires specific sanitation measures in the case of feedstock types of animal origin. Depending on the type of feedstock pre-sanitation by pasteurisation or by pressure sterilisation is required before supplying the substrate to digester. More details about sanitation can be found in Chapter 7.2.

6.2.4 Destruction of weed seeds

A considerable reduction of germination capacity of weed seeds occurs throughout the AD process. This way, biogas production contributes to ecological weed reduction. Experience shows that loss of germination capacity can occur for the majority of weed seeds within 10-16 days HRT, with some differences to be noticed between different types of plant seeds. Like in the case of sanitation, the effect increases with increased retention time and temperature.

6.2.5 Avoidance of plant burns

Application of raw slurry as fertiliser can cause burning of plant leaves, which is the effect of low-density fatty acids, such as acetic acid. When fertilising with digestate, plant burns are avoided, as most fatty acids have been broken down by the AD process. Digestate flows more easily off the plants vegetable parts compared to raw slurry, which reduces the time of direct contact between digestate and the aerial parts of the plants, reducing the risk of leaf damage.

6.2.6 Fertiliser improvement

Through the AD process, most organically bound nutrients, in particular nitrogen, are mineralised and become easily available to the plants. Figure 6.2 shows nitrogen utilisation from digested slurry, applied to winter wheat and spring barley, compared to nitrogen utilisation from untreated slurry. Because of the increased availability of nitrogen, digestate can be integrated in the fertilisation plant of the farm, as it is possible to calculate its fertiliser effects in the same way as for mineral fertilisers.

Digestate has lower C/N ratio, compared to raw manure. Lower C/N ratio means that digestate has a better short term N-fertilisation effect. When the value of the C/N ratio is too high, micro-organisms take hold in the soil, as they successfully compete with the plant roots for the available nitrogen.

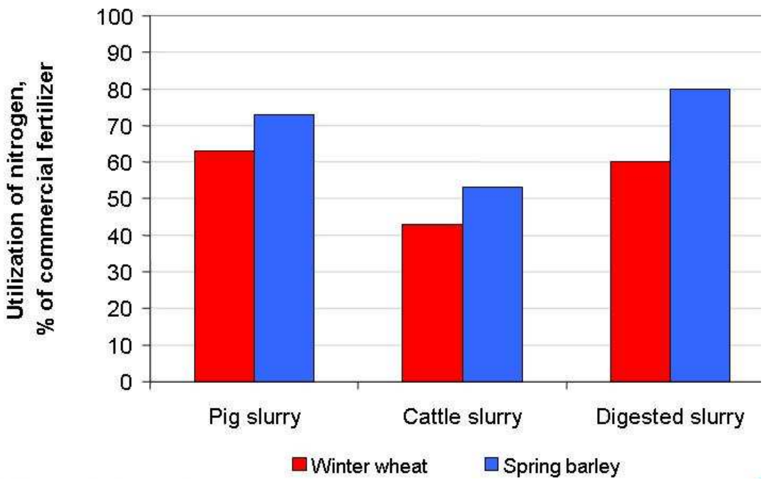

Figure 6.2 Utilisation of nitrogen in digestate compared to untreated pig slurry and cattle slurry (BIRKMOSE 2002)

6.3 Application of digestate as fertiliser

Digestate is more homogenous, compared to raw slurry, with an improved N-P balance. It has a declared content of plant nutrients, allowing accurate dosage and integration in fertilisation plans of farms. Digestate contains more inorganic nitrogen, easier accessible to the plants, than untreated slurry. N-efficiency will increase considerably and nutrient losses by leaching and evaporation will be minimised if digestate is used as fertiliser in conformity with good agricultural practice. For optimum utilisation of digestate as fertiliser, the same practice criteria are valid, like in the case of utilisation of untreated slurry and manure:

- Sufficient storage capacity (minimum 6 months)
- Restricted season of application as fertiliser (during vegetation)
- Amount applied per hectare (according to fertiliser plan)
- Application technique (immediate incorporation and minimum nutrient losses)

Due to its higher homogeneity and flow properties, digestate penetrates in soil faster than raw slurry. Nevertheless, application of digestate as fertiliser involves risks of nitrogen losses through ammonia emissions and nitrate leaking. In order to minimise these risks, some simple rules of good agricultural practice must be respected:

- Avoid too much stirring of digestate before application
- Application of cooled digestate, from the post storage tank
- Application with dragging pipes, dragging hoses, direct injection in soil or disk injectors
- Immediate incorporation in soil, if applied on the surface of soil
- Application at the start of the growing season or during vegetative growth
- Application to winter crops should be started with 1/3 of the total N requirement
- Optimum weather conditions for application of digestate are: rainy, high humidity and no wind. Dry, sunny and windy weather reduces the N-efficiency considerably.

Depending on the crop, experience shows that, in Europe, the best time for digestate application is during vigorous vegetative growth. Application as top-fertiliser on crops in full vegetation offers little concern about loss of e.g. nitrogen as nitrate into ground water, since the main part is absorbed immediately by the plants. Danish experience shows that by application of digestate as top-fertiliser, a part of nutrients are even absorbed through the leaves.

6.4 Effects of digestate application on soil

Degradation of organic matter, which occurs through AD process, includes degradation of carbon bounds, organic acids as well as odoriferous and caustic substances. For this reason, when applied on soil, digestate creates less stress and more suitable environment for soil organisms, compared to application of raw slurry. Direct measurements of biological oxygen demand (BOD) of digested cattle and pig slurry showed ten times less oxygen demand than in the case of undigested slurry. As oxygen consumption is reduced, so is the tendency to form anoxic soil areas, i.e. oxygen free, nitrogen containing zones. The capability to build up new soil and the humus reproduction through supplied organic matter is also higher, when compared to fertilisation with raw slurry.

Good practice guidelines

for minimising ammonia volatilisation, during storage and application of digestate

- **Always have a permanent cover or well established crusting surface/floating layer in the storage tanks for digestate**
- **Digestate should always be pumped at the bottom of storage tanks, to avoid too much stirring; storage tanks should only be stirred just before digestate application**
- **Place the storage tank in the shadow, sheltered from wind**
- **Most emissions can be avoided if digestate is directly injected in soil**
- **For digestate application, dragging hoses should be preferred to sprinkler technologies; sprinkler technologies increase ammonia emissions and spread undesirable aerosols on large areas**
- **Optimum weather conditions for digestate application are: cool, humidity and no wind**
- **Addition of acid to digestate before application decreases its pH-value and thereby the liability of ammonia to volatilise**

Figure 6.3 Vehicles for application of digestate as fertiliser, using dragging hoses (AGRINZ 2008)

Compared to compost and to untreated slurry application, digestate supplies larger portions of carbon, available for the reproduction of organic substances in soils. During AD, decomposable organic bounds such as cellulose and fatty acids are broken down. The lignin bounds, valuable for formation of humus, remain. Methane bacteria themselves produce a whole series of amino acids, which are available for plants and other living organisms in the soil. German studies made with digested pig slurry showed an increase in humus production efficiency index from 0,82 to 1,04.

6.5 Practical experiences

Although there are different opinions among scientists about the effects of applying digestate as fertiliser, especially concerning nitrogen, the existing experience and practice results are unambiguous. For the farmers who use digestate, improvement of fertiliser quality of their own manure and slurry is significant. Conventional farmers observe less use of chemical sprays and reduced amount of purchased chemical fertilisers through integration of digestate in the fertilisation plan.

Browsing deer and hares have been observed on the fields shortly after application of digestate and cattle are also willing to eat the grass from these fields short time after digestate application, both indicating less loss of palatability, compared with application of raw slurry.

As the AD process inactivates most of the weed seeds in animal manure, the spreading cycle of weeds is broken and the amount of weeds on the fields fertilised with digestate is reduced. Farmers which have used digestate as fertiliser over longer periods of time observed an increasing amount of valuable grassland plants on their fields.

Organic farmers, who use AD for the treatment of their own manure and organic wastes, report increased microbiologic soil activity and healthier plants, increased harvest of straw and hay as well as better quality of crops. As organic farming aims to minimise any external input, AD not only provides the farm with higher quality fertiliser, but also with internal renewable energy production, as heat and electricity.

6.6 Digestate conditioning

Digestate has a high water content and consequently high volume. Conditioning of digestate aims to reduce the volume and to concentrate the nutrients. This is particularly important if digestate has to be transported away from the areas where there is an excess of nutrients from animal manure but not sufficient land available for their application. The nutrients in excess must be transported to other areas in an economic and efficient way. Digestate conditioning aims to reduce volume and by this the nutrient transportation costs as well as to reduce emissions of pollutants and odours.

6.6.1 Strategies of digestate conditioning

Digestate can be partially or completely conditioned. Digestion efficiency of agricultural biogas plants is typically of 50-60% (ANGELIDAKI 2004). This means that digestate contains 40-50% of the initial organic dry matter, primarily as fibres.

Partial conditioning means separation of solid matter (fibres) from digestate, using screw type separators or decanters. Partial conditioning by fibre separation was initially done with the aim of producing commercial compost. Later on, full scale trials were made where separated fibre fraction, with dry matter content higher than 45%, was used as supplementary fuel in wood chip boilers, improving the overall energy efficiency by up to 15%, through additional heat production (ANGELIDAKI 2004). A side benefit, which nowadays seems to add to the feasibility of the separation scheme, is the removal and export of excess of phosphorous, which is predominantly attached to the fibre fraction. For this reason, partial conditioning by decanter separation (Table 6.2 and Figure 6.4) is suitable in situations where there is a surplus of phosphorus. The fibre fraction can be exported, whereas the remaining liquid fraction, containing the main part of nitrogen, can be applied as fertiliser. Research results show that separated fibre fractions, mixed with the other co-substrates and fed again to the digester, improve the DM content and the methane potential of the substrate.

Table 6.2 Separated fractions by decanter centrifuge (AL SEADI and MOELLER 2003)

	Amounts %	**DM %**	**N %**	**NH4-N %**	**P %**	**K %**
Raw slurry	**100**	**100** **(6,4%)**	**100** **(5,7%)**	**100** **(4,2%)**	**100** **(1,6%)**	**100** **(2,6%)**
Solid fraction	**14**	**65** **(30%)**	**25** **(10,1%)**	**15** **(4,5%)**	**75** **(8,7%)**	**17** **(3,1%)**
Liquid fraction	**86**	**35** **(2,6%)**	**75** **(4,9%)**	**65** **(4,2%)**	**25** **(0,5%)**	**83** **(2,5%)**

Complete conditioning separates digestate in three refined end products: pure water, concentrated nutrients and organic fibres. All nutrients (nitrogen, phosphorus, and potassium) and organic bounds are separated from the main stream in a low volume, concentrated form. The remaining purified water can be disposed into the surface water system or used as process water. The complete conditioning is particularly suitable for agricultural areas containing nitrogen in excess.

In both cases (partial or complete conditioning), the first step is the separation of liquid and fibre fractions, which divides the digestate into a concentrated carbon and phosphorus enriched solid fraction and a nitrogen rich, fluid fraction. Depending on the plant configuration and the type of conditioning, the complete conditioning further concentrates or separates the NPK nutrients. The most used processes include membrane separation technologies, sorption or stripping of ammonia and evaporation or biological treatment.

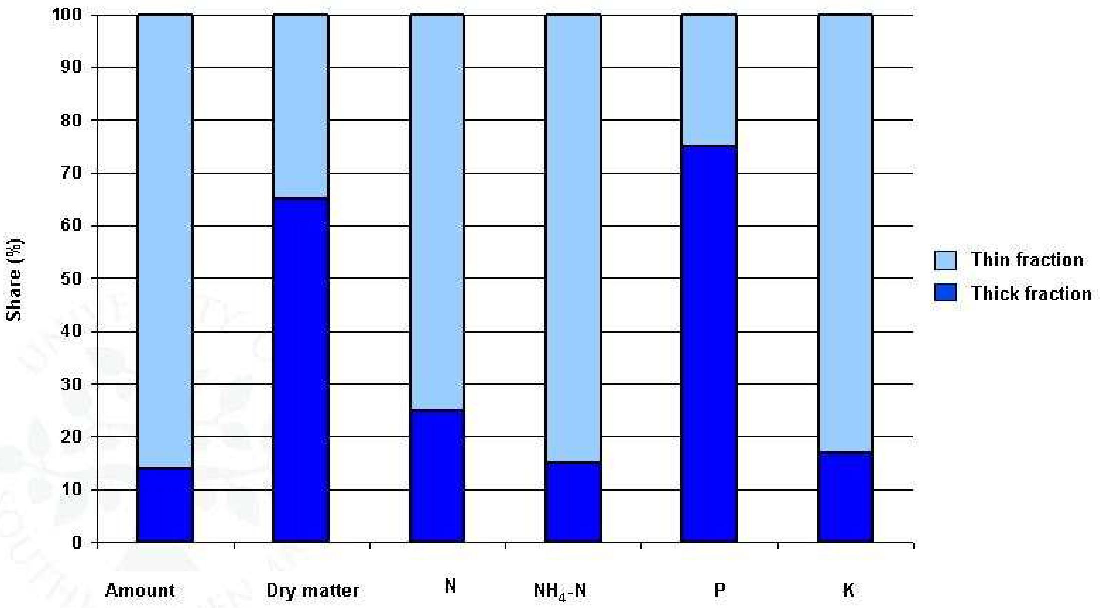

Figure 6.4 Distribution of dry matter and nutrients in separated fractions from decanter centrifuge (AL SEADI and MOELLER 2003)

The fibre separation is done by separators or spiral sieves, decanters and occasionally by ribbon-sieve presses (Figure 6.5). 15-20% of the solids are separated by spiral sieves and more than 60% by decanter centrifuges. Most of nitrogen (up to 90%) is separated with the liquid fraction, while phosphorus is only partially removed, as bonded to the fibre fraction/particles of solid matter.

The total conditioning processes (including water extraction) uses two main technologies: membrane separation technology or evaporation technique. Both are technologically complex and require significant energy consumption. For this reason, they are economically feasible for biogas plants with capacities higher than 700 kW.

Figure 6.5 Fibers collection wagon, with distribution screw (ANGELIDAKI 2004)

Membrane Separation Technology

A membrane is a filter with very fine pores, which can separate particles and solutes from most of the liquids on a molecular scale. The decision to use micro-, ultra-, or nanofiltration or soluble reverse osmosis depends on the size of the particles to be separated. The process is based on the difference of pressure between the two sides of the membrane, i.e. water, as well as minute particles, passing the membrane under pressure. Several conditioning steps are often connected, in successive series, in order to achieve the desired separation. For example, larger particles are removed from a decanter filtrate, through a first step of ultra-filtration and then the solubles are removed in a second step by reverse osmosis. Besides purified water, the membrane separation produces a nutrient rich concentrate, which can be sold either directly as liquid fertiliser, or further processed for volume reduction through evaporation.

Evaporation

Through evaporation, the liquid is further refined and separated into nutrients and purified water. Evaporation units require high energy consumption. In most cases, surplus heat from CHP-production is used in evaporation units, increasing the efficiency of energy utilisation and contributing to financing a part of the operational costs for the conditioning unit.

Crucial for the choice of evaporation technology are the characteristics of the substrate to be evaporated. In the case of digestate, it is possible to use a closed-circulation evaporator, in which the heat transmission and the actual evaporation process run separately. This ensures a more stable process, especially if the substrate to be evaporated has a tendency to produce layers.

6.6.2 Necessary considerations

Conditioning technologies (especially the complete conditioning) require high energy consumption in order to create the pressure used in membrane technologies, or for the production of heat, used in evaporation processes. Up to 50% of the biogas produced electricity is necessary for the complete conditioning of the produced digestate, using membrane technology. Partial conditioning is less energy demanding, cheaper and, in regions where there is a surplus of phosphorus, it is the most economical conditioning technology.

In all the cases, the conditioning technology is chosen according to the chemical and physical characteristics of digestate, herewith the tendency of the digestate to layer formation. If complete conditioning is aimed, it is important that most of the digestible dry matter is removed through complete separation of liquid and fibres, followed by ultra filtration (< 0,2 mm), so that the remaining liquid fraction has almost the quality of pure water. If the separated fractions do not reach the necessary level of purity, or if the chosen membranes and processes are not suitable for digestate, the expenditures for energy, labour, maintenance and cleaning of the system can increase considerably.

6.7 Digestate quality management

6.7.1 Digestate sampling, analyzing and product declaration

Recycling of digestate as fertiliser in agriculture should be done through integration in the fertilization plan of the farm. This implies accurate dosing which is possible because digestate is chemically analysed before leaving the biogas plant. Average samples of all loads of digestate are taken and the content of N, P and K, DM, VM and pH are determined. If the biogas plant co-digests organic wastes, the eventual contamination with heavy metals and persistent organic compounds must be determined also, as their concentration may not exceed the detection limits prescribed by law. Safe recycling as fertiliser requires furthermore that digestate is sanitised, free of prion-transmitted diseases and of physical impurities.

6.7.2 Nutrient management in digestate

One of the important aspects regarding recycling of digestate is the load of nutrients on farmland. Nitrate leaching or phosphorus overloading can occur due to inappropriate handling, storage and application of digestate as fertiliser.

In Europe, the Nitrate Directive (91/676/EEC) restricts the input of nitrogen on farmland, aiming to protect the ground and surface water from nitrate pollution and allows maximum 170 kg N/ha/year. Nutrient loading on farmland is regulated by national legislation in most European countries (Table 6.3).

Table 6.3 Example of national regulations of the nutrient loading on farmland (NORDBERG 1999)

	Maximum nutrient load	Required storage capacity	Compulsory season for spreading
Austria	170 kg N/ha/year	6 months	28/2-25/10
Denmark	170 kg N/ha /year (cattle) 140 kg N/ha/year (pig)	9 months	1/2-harvest
Italy	170-500 kg N/ha /year	90-180 days	1/2- 1/12
Sweden	Based on livestock units	6-10 months	1/2- 1/12

Application of digestate as fertiliser must be done on the basis of a fertiliser plan. The fertiliser plan is elaborated for each agricultural field, according to the type of crop, the planned crop yield, the anticipated utilisation percentage of nutrients in digestate, the type of soil (texture, structure, quality, pH), the existing reserve of macro and micro nutrients in the soil, the pre-crop and the irrigation conditions and the geographic area.

Experience from Denmark indicates that the most economic and environmental friendly strategy of application of digestate as fertiliser is by fulfilling the phosphorus requirement of the crops with phosphorus from digestate. Application of digestate to fulfil the phosphorus requirement implies also a partial fulfilment of nitrogen requirement of the crops. The remaining nitrogen requirement can thus be completed by application of mineral fertiliser.

6.7.3 General measures for quality control and safe recycling of digestate

The experience gathered in Europe with safe recycling of digestate as fertiliser indicates that the aspects listed below should always be considered:

- Permanent control AD process stability (temperature, retention time) to obtain a stable end product (digestate)
- Sanitation of digestate according to European regulation standards, for effective pathogen reduction
- Periodical sampling, analysing and declaration of digestate
- Recycling digestate by integration in the fertiliser plan of the farm and by using *“good agricultural practice”* for application of digestate on farmland

- Careful selection of AD feedstock types and loads, based on complete declaration and description of each feedstock load indicating as a minimum: origin, composition, pH, DM, content of heavy metals and persistent organic compounds, pathogen contamination and other potential hazards

7 Biogas plant components

A biogas plant is a complex installation, consisting of a variety of elements. The layout of such a plant depends to a large extent on the types and amounts of feedstock supplied. As there are many different feedstock types suitable for digestion in biogas plants, there are, correspondingly, various techniques for treating these feedstock types and different digester constructions and systems of operation. Furthermore, depending on the type, size and operational conditions of each biogas plant, various technologies for conditioning, storage and utilisation of biogas are possible to implement. As for storage and utilisation of digestate, this is primarily oriented towards its utilisation as fertiliser and the necessary environmental protection measures related to it.

The main process steps in a biogas plant are outlined in Figure 7.1. The process steps illustrated in italics are not common for agricultural biogas plants. The differentiation in wet and dry AD is only theoretical, since microbiological processes always take place in fluid media. The limit between wet and dry digestion is determined by the “pumpability” of the feedstock. DM content above 15% means that the material is not “pumpable” and the AD in this case is defined as dry digestion. Direct supply of relatively dry feedstock (e.g. maize silage) into the digester increases the DM content of the feedstock mixture.

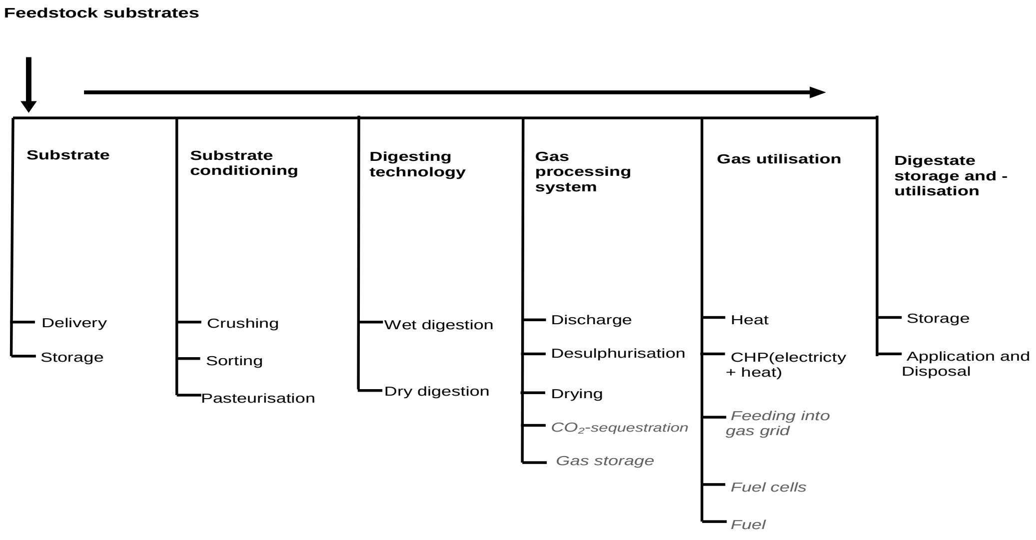

Figure 7.1 Process steps of biogas technologies (LfU 2007)

The core component of a biogas plant is the digester (AD reactor tank), which is accompanied by a number of other components (Figure 7.2).

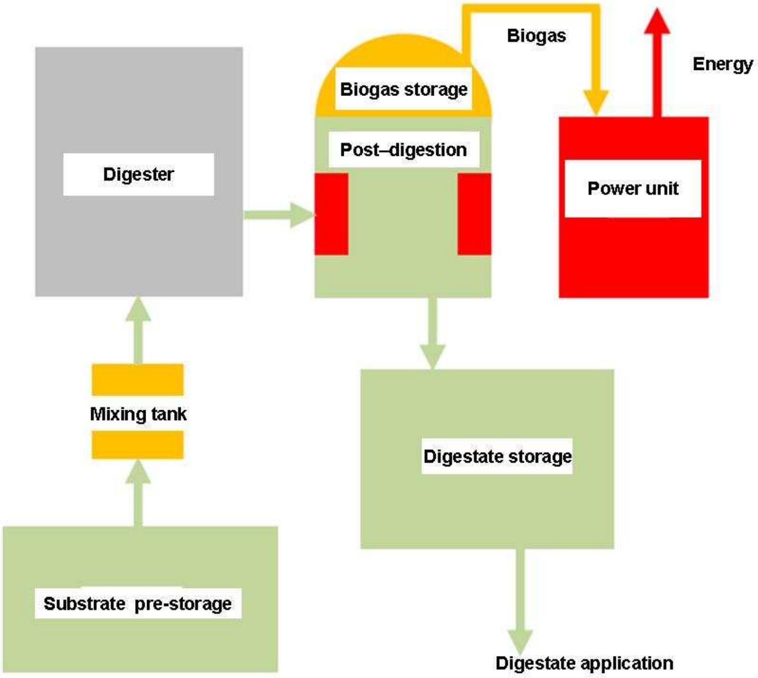

Figure 7.2 Main components and general process flow of biogas production (PRAßL 2008)

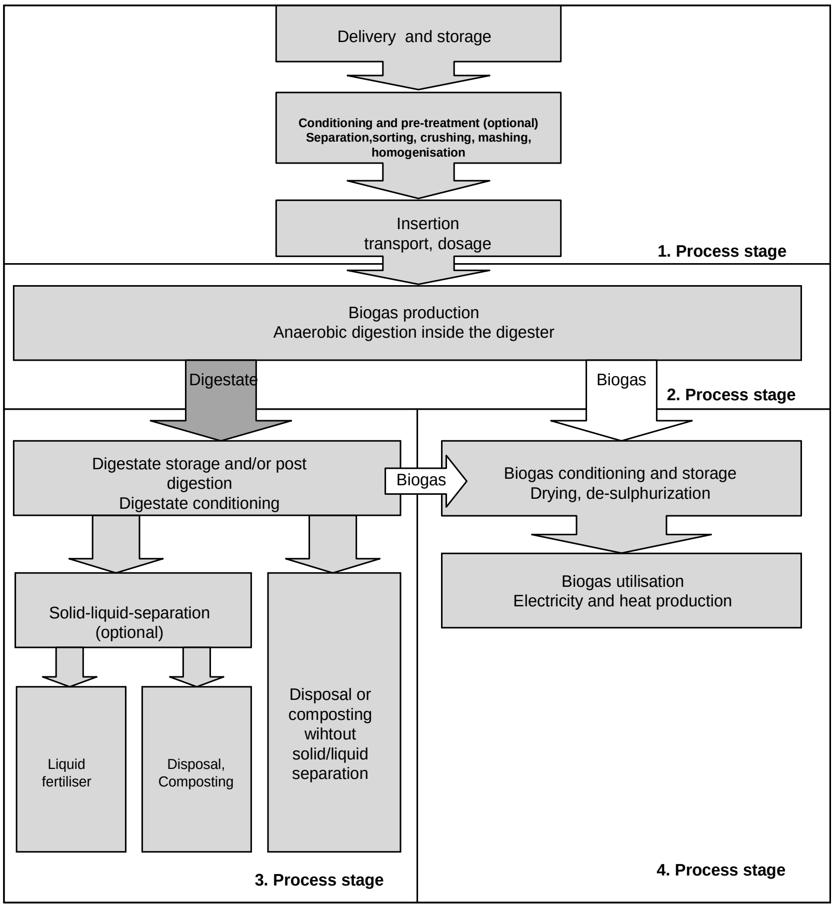

Figure 7.3 Process stages of agricultural biogas plants (JÄKEL 2002)

Agricultural biogas plants operate with four different process stages (Figure 7.3):

1. Transport, delivery, storage and pre-treatment of feedstock
2. Biogas production (AD)
3. Storage of digestate, eventual conditioning and utilisation
4. Storage of biogas, conditioning and utilisation

The process stages shown in Figure 7.3 are further illustrated in Figure 7.4, showing a simplified representation of a typical agricultural co-digestion plant.

1. The first process stage (storage, conditioning, transport and insertion of feedstock) includes the storage tank for manure (2), the collection bins (3), the sanitation tank (4), the drive-in storage tanks (5) and the solid feedstock feeding system (6).
2. The second process stage includes the biogas production in the biogas reactor (7), also referred to as the digester.
3. The third process stage is represented by the storage tank for digestate (10) and the utilisation of digestate as fertiliser on the fields (11).
4. The fourth process stage (biogas storage, conditioning and utilisation) consists of the gas storage tank (8) and the CHP- unit (9).

These four process stages are closely linked to each other (e.g. stage 4 provides the necessary process heating for stage 2).

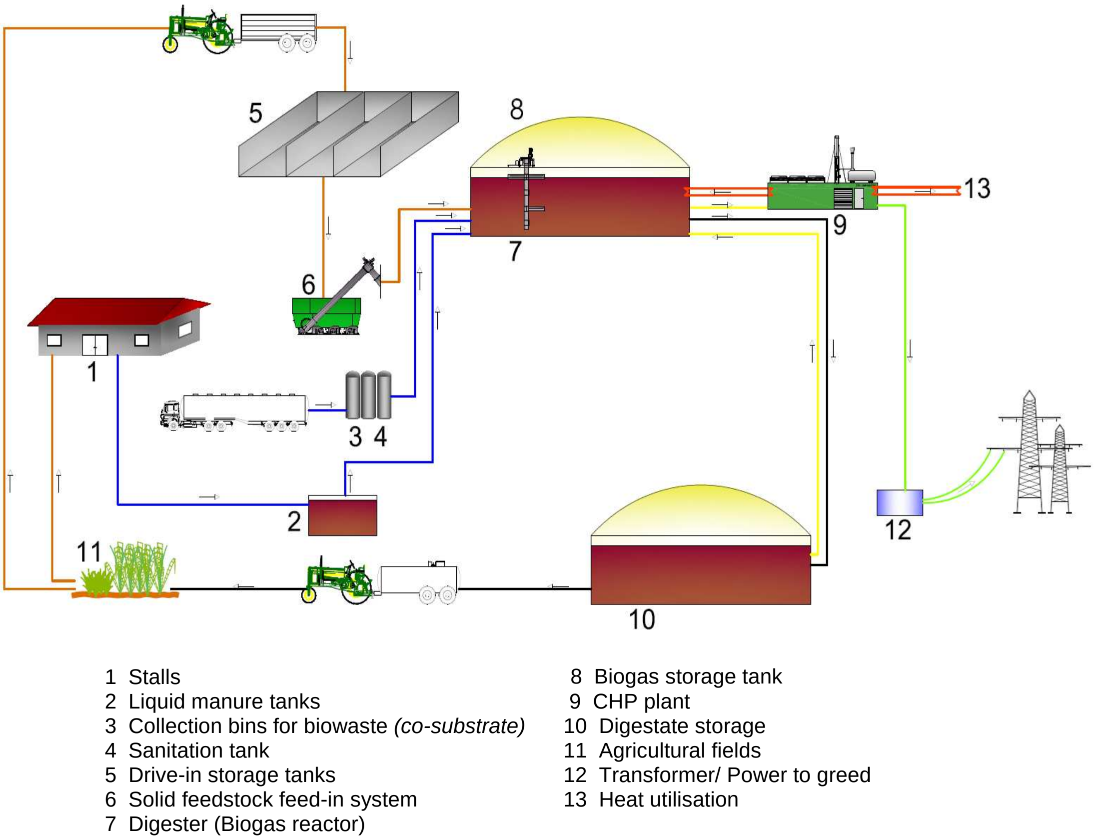

Figure 7.4 Agricultural co-digestion biogas plant using manure and maize silage (LORENZ 2008)

When building a biogas plant, the choice of type and the design of the plant are mainly determined by the amount and type of available feedstock. The amount of feedstock determines the dimensioning of the digester size, storage capacities and CHP unit. The feedstock types and quality (DM-content, structure, origin etc.) determines the process technology.

Depending on the composition of the feedstock, it may be necessary to separate problematic materials, to mash the feedstock or even to add water, in order to convert it into a pumpable mixture. If the supplied feedstock is prone to contamination it is necessary to include a pre-sanitation step in the overall design of the future plant.

In the case of wet digestion, single-stage AD plants, operating with flow-through process are usually used. In the two-stage process, a pre-digester is placed before the main digester. The pre-digester creates the optimal conditions for the first two process steps of the AD process (hydrolysis and acid formation). After pre-digester, the feedstock enters the main digester, where the subsequent AD steps take place.

The digested substrate (digestate) is pumped out of the digester and stored in storage tanks. These storage tanks should be provided with covers of gas proof membranes, to facilitate collection of the biogas production which can take place inside these tanks, at ambient temperature (post-digestion). Alternatively, digestate can be stored in open digestate containers, with natural or artificial floating layer, aimed to minimise surface emissions.

The produced biogas is stored, conditioned and used for energy generation. The actual standard use of biogas is for CHP production in e.g. block-type thermal plants, for the simultaneous production of electricity and heat.

7.1 Feedstock receiving unit

Transport and supply of feedstock plays an important role in the operation of a biogas plant. It is thus important to ensure a stable and continuous supply of feedstock, of suitable quality and quantities. If the biogas plant operator is at the same time the feedstock producer, then the high quality feedstock supply can be easily guaranteed. In many cases, the biogas plants receive additional feedstock (co-substrates), produced by neighbouring farms, industries or households. In these cases, management of feedstock quality is necessary, in order to check, account and verify the supplied material. In a first step, it is absolutely necessary to make visual control of each feedstock load. Then, the delivery weight and all feedstock data (supplier, date, quantity, type of feedstock, processes of origin and quality) should be recorded. Particular attention is needed for feedstock types classified as wastes, for which it may be necessary to fulfil regulatory obligations (depending on the waste category), as well as legal and administrative conditions.

7.2 Feedstock storage and conditioning

7.2.1 Feedstock storage

Feedstock storage serves primarily to compensate the seasonal fluctuations of feedstock supply. It also facilitates mixing different co-substrates for continuous feeding of the digester.

The type of storage facilities depends on the feedstock used. Storage facilities can be mainly classified into bunker silos for solid feedstock (e.g. maize silage) and storage tanks for liquid feedstock (e.g. liquid manure and slurries). Usually, bunker silos have the capacity to store feedstock more than one year and storage tanks for manure have the capacity to store feedstock several days. In some cases, also vertical cylinder silos can be used as well. The dimensioning of the storage facilities is determined by the quantities to be stored, delivery intervals and the daily amounts fed into the digester.

Bunker silos for energy crops

Bunker silos were originally developed to store silage as animal fodder and thus to balance its seasonal availability. Nowadays this type of storage is frequently used for storing the energy crops used as feedstock for biogas production.

Silage must be made from plant material with suitable moisture content (55-70%, depending on the means of storage, degree of compression and water content that will be lost during storage). Silage undergoes a fermentation process where fermentative bacteria use energy to produce VFA such as acetate, propionate, lactate, and butyrate, which preserve the silage. The result is that silage has lower energy content than the original plant material, as fermentative bacteria use some of the carbohydrates to produce VFA.

In countries like Germany, silage is stored in bunker silos, made of concrete (Figure 7.5) or in large heaps on the ground (Figure 7.6). The silage is rolled by tractor in order to pack it as firmly as possible and by this to press out the air. Minimising the oxygen content is necessary in order to avoid aerobic processes. For the same reason, the silage is usually covered by plastic foils, held tight by tyres or sand bags. Alternatively, natural covers can be established, such as a layer of grass silage, which can also tighten the bunker silo. On some silos also wheat is planted and some silos are not covered at all. This reduces costs for the cover, but increases energy losses from the silage.

In the case of bunker silos, it must always be considered that the fermentation process of the silage releases liquids which can contaminate water courses, unless precautions are taken. The high nutrient content can lead to eutrophication of surface waters (growth of algae blooms). Silo effluent contains nitric acid (HNO_3), which is a corrosive compound.

Figure 7.5 Bunker silo (WIKIPEDIA 2008)

Figure 7.6 Corn silage stored on a large heap on the ground, covered by a layer of grass silage (RUTZ 2007)

Storage tanks for pumpable feedstock

Pumpable feedstock is generally stored in sealed, water-tight and reinforced concrete tanks in or above the ground. These tanks, similar to the ones used in agriculture, for storage of liquid manure, usually have a storage capacity sufficient for one to two days. To prevent emissions, all storage tanks should be covered. The chosen solution for cover must ensure easy opening and removal of settled sediments. If storage tanks are placed on a higher level compared to the digester (sloping topography), the hydraulic incline eliminates the need for transport equipment (pumps) and saves energy.

Co-substrates (liquid or stackable) can be mixed with the main substrates inside the storage tank, crushed, homogenised and transformed into a pumpable mixture. Clogging, sedimentation, floating layers and phase separation of the feedstock mixture must be avoided. For this reason, storage tanks are outfitted with stirrers often combined with tearing and cutting tools for crushing the feedstock. Stirring of storage tanks is done with the same stirring technique which is used for stirring the digesters.

Storage tanks for pumpable feedstock require limited maintenance, this including removal of sediment layers of sand and stones, which reduce the storage capacity of the tanks. Sediments are removed using scrape floors, conveyor screws, sump pumps, collection tanks or countersink aggregates.

Feedstock types of industrial origin can require sanitation measures and must therefore always be handled and stored strictly separated from the delivery station for agricultural feedstock, in order to prevent mixing critical feedstock with non-critical feedstock, before processing in the sanitation equipment.

In order to minimise odours from the biogas plant as well as for practical reasons, delivery, storage and preparation of feedstock must take place in closed halls, equipped with biofilter ventilation. The equipment is thereby protected and operation, as well as monitoring activities can be carried out regardless of weather conditions.

7.2.2 Feedstock conditioning

Feedstock conditioning influences the flow and the efficiency of AD process. The main aim of conditioning is to fulfil the demands of sanitation and to increase feedstock digestibility.

Feedstock conditioning offers significant potential for process optimisation, increases digestion rates and biogas yields. There are several possibilities for conditioning the feedstock and optimising the organic load of the plant such as mechanical crushing, disintegration processes (already used in sewage treatment), hydrolysis etc.

Feedstock sorting and separation

The necessity of sorting and separating impurities and problematic materials from the feedstock substrate depends on the origin and composition of the feedstock. Silage is among the cleanest feedstock types while e.g. manure and household wastes can contain stones and other physical impurities. These are usually separated by sedimentation in storage tanks (and in the case of sand, even inside the digesters) and they have to be removed from the bottom of the tanks from time to time. A pre-tank outfitted with special grills, able to retain stones and other physical impurities before pumping the feedstock into the main storage tank, is used in many cases.

Household waste, catering and food wastes can contain various impurities (packing and wrapping residues of plastic, metal, wood, glass and other non-digestible materials (Figure 7.7 right), which can cause damage on pumps, block pipes and even the digesters. These impurities can be removed by a separate collection system of e.g. household wastes or they can be removed from bulk collected wastes by mechanical, magnetic and manual methods.

Figure 7.7 Feed-in system for cleaning municipal solid waste (*left*) and "problematic material" which was separated from catering wastes (*right)* (RUTZ 2007)

Sanitation

Handling, treatment and recycling of digestate must be done safely, without contamination risks for humans, animals or the environment. European and national legislations regulate waste treatment practices with regard to epidemic and hygienic risks, prescribing the suitable sanitation treatment for critical materials. For further details see chapter 9.4.4. In all cases, sanitation of specific AD feedstock types must be done before pumping the respective feedstock in the digester. The reason is to avoid contamination of the whole feedstock load and to keep sanitation costs low. Sanitation is usually carried out in separate, heated stainless steel tanks, connected to the digester feeding system. Typical monitoring parameters for sanitation include temperature, minimum guaranteed retention time (MGRT), pressure and volume. The temperature of the material after the sanitation process is higher than the AD process temperature. For this reason and before being fed into the digester, the sanitised material should pass through a heat exchanger, where some of the heat is transferred to the fresh biomass, which is pumped in the digester.

Crushing

Feedstock crushing prepares the surfaces of the particles for biological decomposition and the subsequent methane production. As a general rule, the decomposition process is faster when the particle size is smaller. However, particle size only influences digestion time, but does not necessarily increase methane yields. Feedstock crushing is usually directly connected to the feeding system. Both can be powered by an electric motor or by the drive shaft of a tractor.

Mashing, homogenising

Mashing of feedstock can be necessary in order to obtain feedstock with a higher water content, which can be handled by pumps. Mashing takes place in storage tanks or pre-digesters, before pumping the material into the main digester. Liquids used for the mashing process depend on availability and are usually raw liquid manure, digestate, process water or even fresh water.

The advantage of using digestate for mashing lies in the reduction of fresh water consumption and in the inoculation of the substrate with AD micro-organisms from the digester. This can be important after sanitation or in the plug-flow-process (shot plug process). However, using digestate for mashing can consequently increase nutrient and salt content in the substrate and lead to process imbalance or inhibition. The same precautions must be taken if water from cleaning processes is used for mashing, as disinfectants can have a negative impact on AD microorganisms. Use of fresh water should always be avoided due to high costs.

Besides pumpability, substrate homogeneity is another important factor for the stability of the AD process. The already pumpable feedstock is homogenised by stirring the storage tank while solid feedstock must be homogenised during the feeding process. Large fluctuations of the supplied feedstock types and of feedstock composition stress the AD microorganisms, as they have to adapt to new substrates and to changing conditions. Experience shows that usually this results in lower gas yields, thus it is important to have a stabile and constant supply of feedstock, over a long period of time, in order to have a balanced and “healthy” AD process, with a high methane yield.

7.3 Feeding system

After storage and pre-treatment, AD feedstock is fed into the digester. The feeding technique depends on the feedstock type and its pumpability. Pumpable feedstock is transferred from storage tanks to the digester by pumps. The pumpable feedstock category includes animal slurries and a large number of liquid organic wastes (e.g. flotation sludge, dairy wastes, fish oil). Feedstock types which are non-pumpable (fibrous materials, grass, maize silage, manure with high straw content) can be tipped/ poured by a loader into the feeding system and then fed into the digester (e.g. by a screw pipe system). Both feedstock types (pumpable and non-pumpable) can be simultaneously fed into the digester. In this case it is preferable to feed the non-pumpable feedstock through by-passes.

From a microbiological point of view, the ideal situation for a stable AD process is a continuous flow of feedstock through the digester. In practice, the feedstock is added quasi-continuously to the digester, in several batches during the day. This saves energy as feeding aggregates are not in continuous operation. There are various feeding systems and their selection depends again on feedstock quality, herewith their pumpability and on feeding intervals.

Special attention must be paid to the temperature of the feedstock which is fed into the digester. Large differences between the temperature of the new feedstock and the operation temperature of the digester can occur if the feedstock has been sanitised (up to 130°C) or during winter season (below 0°C). Temperature differences disturb the process microbiology, causing losses of gas yield and must therefore be avoided. There are several technical solutions to this problem, such as using heat pumps or heat exchangers to pre-heat /cool the feedstock before insertion in the digester.

7.3.1 Pumps for transport of pumpable feedstock

The transfer of pumpable feedstock substrate from the storage tank into the digester is done by pumps. Two types of pumps are frequently used: the centrifugal and the displacement pumps. Centrifugal (rotating) pumps are often submerged, but they can also be positioned in a dry shaft, next to the digester. For special applications, cutting pumps are available, which are used for materials with long fibres (straw, feed leftovers, grass cuttings). Displacement pumps (turning piston pumps, eccentric screw pumps) are more resistant to pressure than rotating pumps. They are self-sucking, work in two directions and reach relatively high pressures, with a diminished conveying capacity. However through their lower price, rotating pumps are more frequently chosen than displacement pumps.

Centrifugal pumps

A centrifugal pump is a roto-dynamic pump, using a rotating impeller to increase the velocity of a fluid. The fluid enters the pump impeller along or near the rotating axis and is accelerated by the impeller, flowing radially outward into a diffuser or volute chamber, from where it exits into the downstream piping system. Centrifugal pumps are commonly used to move liquids through a piping system and are therefore frequently used for handling liquid manure and slurries.

Pressure displacement pumps

For the transport of thick liquid feedstock, with high dry matter content, pressure displacement pumps (rotary piston and eccentric screw pumps) are often used. The quantity of transported material depends on the rotation speed, which enables better control of the pump and precise dosing of the pumped feedstock. Displacement pumps are self-sucking and more pressure stable than centrifugal pumps. For this reason, the piping performance is less dependent on difference in height. As pressure displacement pumps are relatively prone to problems caused by high fibre content in pumped materials, it makes sense to equip them with cutters and separators, to protect them from large particle size and fibrous materials.

The selection of appropriate pumps and pumping technology depends on the characteristics of the materials to be handled by pumps (type of material, DM content, particle size, and level of preparation). Biogas plants use the same pumps that are used for liquid manure, which proved to be suitable for feeding the digester and for handling the digested substrate. Practical experience indicates that formation of plugs at inlet and outlet can be prevented by a sufficient diameter of the pipes. Pressure pipes, for filling or mixing, should have a diameter of at least 150 mm, while pressure free pipes, like overflow or outlet pipes, should have at least 200 mm for transporting manure and 300 mm if the straw content is high.

All movable parts of the pumps are subjected to high wear and must therefore be replaced from time to time. This should be feasible without interrupting biogas production. For this reason, the pumps must be equipped with stop-valves (Figure 7.8), which allow feeding and emptying of digesters and pipelines. Pumps and pipes should be easily accessible and ensure sufficient working room, to perform the maintenance work.

The function of pumps, and by this the transport of pumpable substrate, is controlled automatically, using process computers and timers. In many cases the entire feedstock transport within the biogas plant is realised by one or two pumps, located in a pumping station (Figure 7.8 right and 7.9).

Figure 7.8 Stop-valves (*left*) and pumping system (*right*) (RUTZ 2006)

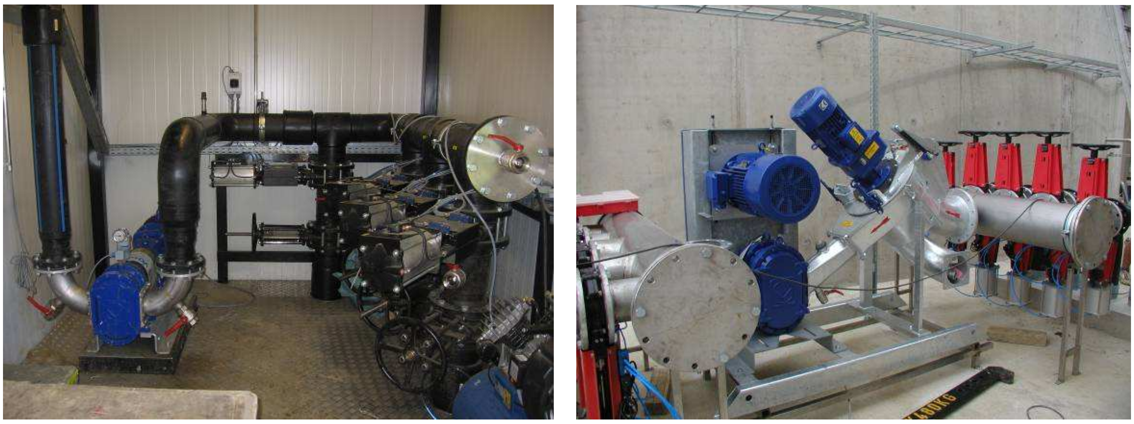

Figure 7.9 Pumping systems (AGRINZ 2008)

7.3.2 Transport of stackable feedstock

Stackable feedstock like grass, maize silage, manure with high straw content, vegetable residues etc. must to be transported from a storage facility (bunker silo) to the digester feed-in system. This is usually done by loaders or tractors (Figure 7.10 and 7.11) and the feedstock is fed into the digester using e.g. a screw pipe transporting system, like the ones shown in Figure 7.12.

The feed-in system includes a container, where stackable feedstock is poured by tractor, and a transport system, which feeds the digester. The transport system is controlled automatically and consists of scraper floors, walking floors, pushing rods and conveyor screws.

Scraper floors and overhead push rods are used to transport feedstock to the conveyor screws. They are capable of transporting nearly all stackable feedstock, either horizontally or with a slight incline, and are therefore used in very large, temporary storage containers, but they are not suitable for dosing.

Conveyor screws can transport feedstock in nearly all directions. The only precondition is the absence of large stones and other physical impurities. For optimal function, coarse feedstock should be crushed, in order to be gripped by the screw and to fit into the screw windings.

Figure 7.10 Feed-in container system for dry feedstock -maize silage and solid poultry manure- (*left*) and loader with maize silage (*right*) (RUTZ 2008)

Figure 7.11 Loader feeding maize silage into a container (RUTZ 2008)

Figure 7.12 Screw pipe transporting system (*left*) and conveyor screws, ready for installation (*right*) (RUTZ 2007)

The insertion of the feedstock into the digester has to be air-tight and should not allow leak of biogas. For this reason, the feed-in system inserts the feedstock below the surface layer of digestate (Figure 7.13). Three systems are commonly used: wash-in shaft, feed pistons and feed conveyor screws.

Wash-in shaft

Feeding solids to the digester through wash-in shafts or sluices, using front or wheel loaders, allows large quantities of solids to be delivered any time, directly to the digester (Figure 7.13).

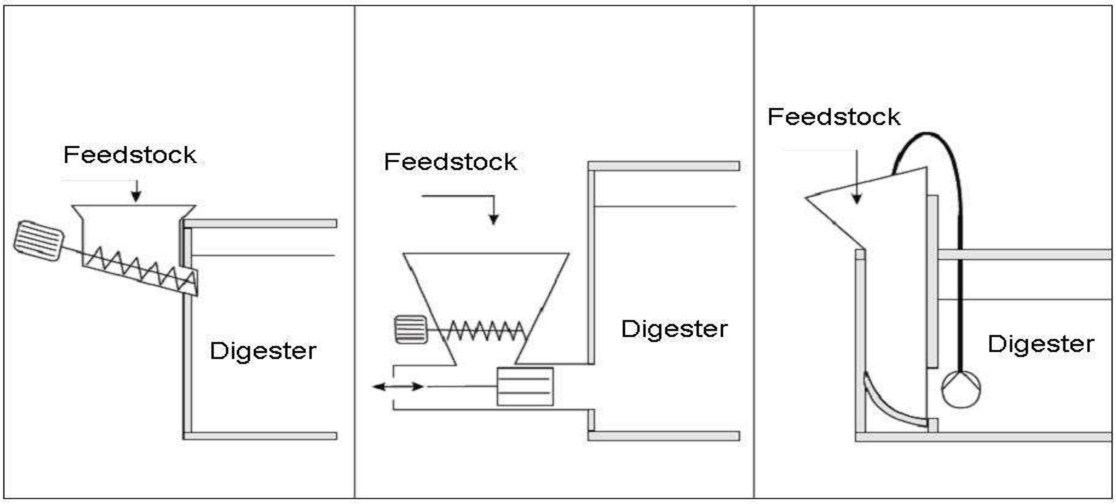

Figure 7.13 Wash-in shaft, feed pistons and feed conveyors system for feedstock insertion into the digester (FAL 2006)

Feed pistons

When using feed pistons (Figure 7.13), the feedstock is inserted directly into the digester by hydraulic cylinders, which push the feedstock through an opening in the wall of the digester. This ground level insertion means that the feedstock is soaked in the liquid content of the digester, reducing the risk of floating layer formation. This system is equipped with counter-rotating mixing rollers, which transport co-substrates to the lower horizontal cylinders and, at the same time, crush long fibre materials.

Feed conveyor screws

Feeding co-substrates to the digester can be done by using feed screws or conveyor screws (Figure 7.13). In this case, the material is pressed under the level of the liquid in the digester, using plug screws. The method has the advantage of preventing gas leaking during feeding. The simplest way to do it is to position a dozer on the digester, so that only one insertion screw is necessary. For feeding the screw, temporary storage containers, with and without crushing tools, are used.

Figure 7.14 Feed-in system for silage (AGRINZ 2006)

7.4 Armatures and pipelines

The armatures and pipelines used in biogas installations must be corrosion proof and suitable to handle specific types of materials (biogas and biomass). The materials used for pipelines depend on the transported load and pressure level and they include PVC, HDPE, steel and stainless steel. Armatures such as couplings, slide valves, butterfly valves, cleaning openings and manometers must be accessible, easy to maintain and placed frost free. In some cases insulation of pipes is necessary (Figure 7.15). For safe operation of biogas installations, minimum requirements for pipelines and armatures have to be guaranteed, with regard to their material properties, safety features and tightness.

Biomass pipelines should have a diameter of 300 mm. Back flow of substrate, from digester into storage tanks, is prevented through appropriate pipeline layout. When installing the pipes, an incline of 1-2% should be maintained, in order to allow complete clearance. Proper sealing of the installation is a must. Long and angled pipelines are susceptible to loose pressure.

Figure 7.15 Insulated gas pipelines -*left*; Pipelines for digestate handling -*right* (RUTZ 2008)

Gas pipelines must be installed sloped and be outfitted with valves, in order to release the condensate. Even very small amounts of condensate could lead to complete blockage of gas lines due to low pressure in the system.

7.5 Heating system - digester heating

Constant process temperature inside the digester is one of the most important conditions for stable operation and high biogas yield. Temperature fluctuations, including fluctuations determined by season and weather conditions as well as local fluctuations, in different areas of the digester, must be kept as low as possible. Large fluctuations of temperature lead to imbalance of the AD process, and in worst cases to complete process failure.

The causes of temperature fluctuations are various:

- Addition of new feedstock, with different temperature than the one of the process
- Formation of temperature layers or temperature zones due to insufficient insulation, ineffective or incorrect dimensioning of heating system or insufficient stirring
- Inadequate placement of heating elements
- Extreme outdoor temperatures during summer or winter
- Failure of power-trains

In order to achieve and maintain a constant process temperature and to compensate for eventual heat losses, digesters must be insulated and heated by external heating sources (Figure 7.16). The most frequently used source is waste heat from the CHP unit of the biogas plant.

Heating the feedstock can be done either during the feeding process (pre-heating), through heat exchangers or it can be done inside the digester, by heating elements (Figure 7.17.), hot steam etc. Pre-heating the feedstock during feeding has the advantage of avoiding temperature fluctuations inside the digester. Many biogas plants use a combination of both types of feedstock heating.

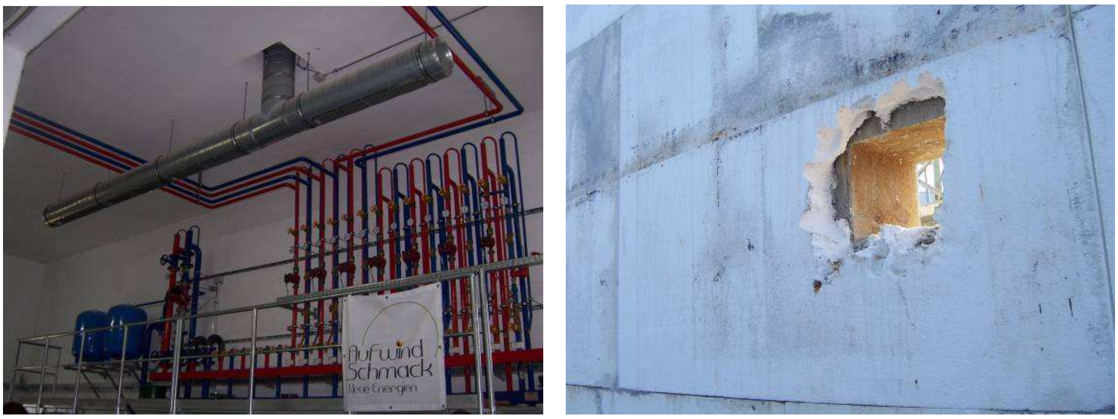

Figure 7.16 Heating system of a biogas plant (*left*) and insulation of a concrete digester, under construction (*right*) (RUTZ 2008)

Figure 7.17 Heating pipes, installed inside the digester (AGRINZ 2008)

7.6 Digesters

The core of a biogas plant is the digester - an air proof reactor tank, where the decomposition of feedstock takes place, in absence of oxygen, and where biogas is produced. Common characteristics of all digesters, apart from being air proof, are that they have a system of feedstock feed-in as well as systems of biogas and digestate output. In European climates anaerobic digesters have to be insulated and heated.

There are a various types of biogas digesters, operating in Europe and around the world. Digesters can be made of concrete, steel, brick or plastic, shaped like silos, troughs, basins or ponds, and they may be placed underground or on the surface. The size of digesters determine the scale of biogas plants and varies from few cubic meters in the case of small household installations to several thousands of cubic meters, like in the case of large commercial plants, often with several digesters.

The design of a biogas plant and the type of digestion are determined by the dry matter content of the digested substrate. As mentioned before, AD operates with two basic digestion systems: wet digestion, when the average dry matter content (DM) of the substrate is lower than 15 % and dry digestion, when the DM content of the substrate is above this value, usually between 20-40 %. These definitions and their limit values have some regional variations or they can be differentiated by legislation and support schemes, like e.g. in Germany.

Wet digestion involves feedstock like manure and sewage sludge, while dry digestion is applied to biogas production from solid animal manure, with high straw content, household waste and solid municipal biowaste, green cuttings and grass from landscape maintenance or energy crops (fresh or ensiled). Both dry and wet digesters are described in the next subchapters, with emphasis on wet digestion systems.

From the point of view of feedstock input and output, there are two basic digester types: batch and continuous.

7.6.1 Batch-type digesters

The specific operation of batch digesters is that they are loaded with a portion (batch) of fresh feedstock, which is allowed to digest and then is completely removed. The digester is fed with a new portion and the process is repeated. Batch-type digesters are the simplest to build and are usually used for dry digestion.

An example of batch digesters are the so-called "*garage type*" digesters (Figure 7.18) made of concrete, for the treatment of source separated biowaste from households, grass cuttings, solid manure and energy crops. Treatment capacity ranges from 2 000 to 50 000 tonnes per year. The feedstock is inoculated with digestate and fed in the digester. Continuous inoculation with bacterial biomass occurs through recirculation of percolation liquid, which is sprayed over the substrate in the digester.

Unlike wet digestion, dry digestion needs no stirring or mixing of the AD substrate during digestion. The temperature of the process and of percolation liquid are regulated by a built-in floor heating system, inside the digester, and by a heat exchanger, which acts as a reservoir for percolation liquid.

Compared to other systems, batch digestion has the advantage of low operation costs and costs of the mechanical technology behind it and the disadvantage of high process energy consumption and maintenance costs.

Figure 7.18 Garage-type batch digester, loaded by a loader (BEKON 2004)

A promising alternative for complete dry digestion is the use of plastic bags or foil tubes. The idea is to reduce investment costs by using plastic sheeting from silo bag technology, where AD substrates (manure, biowastes, DEC) are stored in airtight plastic bags.

Batch digesters are also used for combined dry and wet digestion, in case of stackable feedstock types, where additional waste water or percolation liquid is used in larger quantities for flooding or percolation.

The possibility to handle substrates, not only through pre-treatment and percolation, but also by high pressure "aeration" and flooding, enables dry fermentation to be used as a suitable treatment process for controlled landfills.

7.6.2 Continuous-type digesters

In a continuous-type digester, feedstock is are constantly fed into the digester. The material moves through the digester either mechanically or by the pressure of the newly feed substrate, pushing out the digested material. Unlike batch-type digesters, continuous digesters produce biogas without interruption for loading new feedstock and unloading the digested effluent. Biogas production is constant and predictable.

Continuous digesters can be vertical, horizontal or multiple tank systems. Depending on the solution chosen for stirring the substrate, continuous digesters can be completely mixed digesters and plug flow digesters (Table 7.1). Completely mixed digesters are typically vertical digesters while plug-flow digesters are horizontal.

Table 7.1 Digester types

Completely mixed digesters	**Plug flow digesters**
Round, simple tank construction, vertical	Elongated, horizontal tank
Completely mixed	Vertically mixed
Suitable for simple feedstock (liquid manure)	Suitable for difficult feedstock (solid manure)
Fractions of the undigested feedstock can reach the outflow	Normally, no short cut between inflow and outflow; secure sanitation
Process temperature 20° - 37° C	Process temperature 35° - 55° C
Retention time 30 - 90 days	Retention time 15 - 30 days

Vertical digesters

In practice, most digesters are vertical digesters. Vertical digesters are generally built on-site (Figure 7.19), round tanks of steel or reinforced concrete, often with a conic bottom, for easy stirring and removal of sand sediments. They are air proof, insulated, heated and outfitted with stirrers or pumps. The digesters are covered by a roof of concrete, steel or gas proof membrane and the produced biogas is piped and stored in an external storage facility, close to the digester or under the gas proof membrane. The membrane is inflated by the produced biogas or it can be fastened to a central mast (Figure 7.20).

Figure 7.19 On-site construction of vertical digesters (RUTZ 2007)

Digesters made of reinforced concrete are sufficiently gas tight due to water saturation of the concrete from the moisture contained in feedstock and biogas. Concrete tanks can be built completely or partially in the ground. Improper construction can lead to cracking, leakage, corrosion and in extreme cases to the demolition of the digester. These problems can be avoided by using appropriate concrete quality and professional planning and construction of the digester.

Figure 7.20 Vertical digesters, covered by gas proof membrane. The membrane top is inflated by the produced biogas –*left* (AGRINZ 2008); The membrane top is fastened to a central mast –*right* (RUTZ 2006)

Steel digesters are installed on a concrete foundation. Steel plates are either welt or bolted together and seams have to be tightened. Steel digesters are always installed above ground.

The advantage of vertical digesters is that the existing manure tanks at the farms can be converted cost effectively into biogas digesters by adding the insulation and the heating system. For later insulation, waterproof insulating plates (styrofoam) are connected with plugs on the inner walls of the tank. Another option for insulation of former manure tanks is the complete foaming of the inside of the tank, for gas tightness, operation which must be done by specialised firms. The tanks are finally covered with a gastight roof of single or double membrane.

A special AD system, used for agricultural biogas plants treating animal manure, is the so-called accumulation-continuous-flow-systems (ACF system). In this system, the entire manure tank serves at the same time as digester and as storage facility for manure. These kinds of plants were installed on farms where mandatory storage capacities had to be built. The minimum load is reached in summer, after the last application of digestate as fertiliser.

During fall and winter the digester is filled up. In this stage, the system works with a continuous flow and has a high retention time and good gas yields. Digestate flows into the storage tank which works also as post digester.

Horizontal digesters

Horizontal digesters (Figure 4.3, page 33 and Figure 7.21) have a horizontal axis and a cylindrical shape. This type of digesters are usually manufactured and transported to the biogas plant site in one piece, so they are limited in size and volume. The standard type for small scale solutions is a horizontal steel tank of 50-150 m^3, which is used as the main digester for smaller biogas plants or as pre-digesters for larger plants. There is also an alternative of concrete, the channel type digester, which allows a larger digester volume of up to 1 000 m^3.

Horizontal digesters can also run in parallel, in order to achieve larger throughput quantities. Because of their shape, the plug-flow stream is automatically used. The feedstock flows slowly from the entry side to the discharge side, forming a plug-flow, streaming through the digester. The risk of discharging un-decomposed substrate is minimised through a minimum guaranteed retention time (MGRT) of the substrate inside the digester. Horizontal continuous flow digesters are usually used for feedstock like chicken manure, grass, maize silage or manure with a high straw content.

The insulated digester is equipped with a heating system, gas dome, manure pipes and stirrer. The heating system consists of stirring heat pipes, with a warm water supply-drain or of diagonally built-in radiators. The arms of the slow mowing paddle stirrer are spirally arranged on the stirring axle, in order to insure an equal distribution of the torque. The big number of paddles is able to transport sand fallout to the drain tanks. By ensuring a continuous in and out flow of the feedstock, an HRT of 15-30 days can be obtained. The filling level of the digester always reaches the same height and will fluctuate within the gas dome during filling and stirring. The level is regulated by a siphon at the outflow. The digester is fitted out with a weatherproof cover or placed under a roof. It can be built up either on site or manufactured as a small series product. Digesters of steel and stainless steel are always manufactured above ground and placed on and fastened to a concrete foundation. The screw connections have to be sealed.

Multiple tank systems

Large farm scale co-digestion plants usually consist of several digester tanks. They are normally operated as continuous flow system, including one or several main digesters and post digesters. Like in the case of single digesters, the multiple tank system can consists of vertical digesters only or a combination between vertical and horizontal digesters. The storage tanks for digestate serve also as post-digesters and should always be covered with gas tight membrane.

Figure 7.21 Horizontal plug-flow digester (RUTZ 2006)

7.6.3 Maintenance of digesters

Removal of sediments in the digester

Sediments of heavy materials such as sand and other non-digestible materials can accumulate inside continuous-type digesters. Most of these materials can be removed during pre-storage or during the feeding process. However, sand can be very strongly attached to organic matter, thus difficult to separate prior to digestion. A large portion of this sand is released during the AD process in the digester. Animal manure (pig slurry, chicken dung), but also other types of biomass can contain various amounts of sand. Accumulation of sand inside the tanks and digesters reduces their active volume. The presence of sand in the biomass flow is heavily loading the stirring systems, the pumps and the heat exchangers, causing fouling, obstructions and heavy wear. If not removed periodically, sediment layers can become hard and can only be removed with heavy equipment. Continuous removal of sediment layers from digesters can be done using floor rakes or a floor drain. If the amount of sediment formation is high, the sediment removal systems may not function and the digester must be taken out of operation and opened in order to remove the sediment layer manually or mechanically, according to the size of the digester. The static pressure of very high digesters (more than 10 m) is considered sufficient to remove sand, scale and sludge.

Sediment formation and the problems caused by it can be minimised by some basic measures:

- Regularly emptying of pre-storage and storage tanks
- Establishing sufficient pre-storage capacity
- Applying adequate stirring method
- Adequate placement of the pumping pipe stubs, in order to avoid sand circulation
- Avoiding feedstock types with high sand content
- Utilisation of specially developed methods of sand evacuation from the digesters

Measures against foam layers

Forming of foam and swimming layers can be a sign of process imbalance and their formation is often caused by the types of feedstock supplied. The presence of foam and swimming layers on the surface of biomass, inside the digester, can cause clogging of gas lines. To prevent this, gas lines should be installed as high as possible inside the digester. Foam traps can prevent penetration of foam in the feedstock pipes and to the post digester or storage basins. A foam sensor can be installed in the gas area of the digester, to start automatically spraying foam retardant inside the digester, if there is too much foam on the surface of the substrate. The foam retardants must be used only in emergency situations, as they usually consist of silicate binders which can damage the CHP plant.

7.7 Stirring technologies

A minimum stirring of biomass inside the digester takes place by *passive stirring*. This occurs by insertion of fresh feedstock and the subsequent thermal convection streams as well as by the up-flow of gas bubbles. As passive stirring is not sufficient for optimal operation of the digester, active stirring must be implemented, using mechanical, hydraulic or pneumatic equipment. Up to 90% of biogas plants use mechanical stirring equipment.

The digester content must be stirred several times per day with the aim of mixing the new feedstock with the existing substrate, inside the digester. Stirring prevents formation of swimming layers and of sediments, brings the micro-organisms in contact with the new feedstock particles, facilitates the up-flow of gas bubbles and homogenises distribution of heat and nutrients through the whole mass of substrate.

Stirrers can run continuously or in sequences. Experience shows that stirring sequences can be empirically optimised and adapted to a specific biogas plant (tank size, feedstock quality, tendency to form floating layers etc.). After the supply of the first feedstock load and the start-up of the plant, the optimum duration and frequency of stirring sequences and adjustment of stirrers will be determined by experience, through continuous monitoring of digester performance.

Experience from Denmark shows that submerged, electrically driven, medium speed stirrers, largely utilised in the past, proved relatively expensive in operation and difficult to access for service and inspection. A better alternative proved to be the continuously, slow rotating stirrers, installed centrally, in the top of the digesters, although their utilisation requires a precise adjustment of the level of biomass inside the digester, in order to avoid formation of floating layers.

7.7.1 Mechanical stirring

According to their rotation speed, mechanical stirrers can be intensive fast running stirrers, medium running stirrers and slow running stirrers.

Figure 7.22 Submersible motor propeller stirrer (AGRINZ 2006)

Figure 7.23 Hanging paddle stirrers (*left*) and its stirring engine (*right*) (AGRINZ 2006)

Figure 7.24 Paddle stirrers (AGRINZ 2006)

Submersible motor propeller stirrers (Figure 7.22) are frequently used in vertical digesters. The stirrers are driven by gearless electric motors, with water-tight housings and anticorrosive coatings, which are cooled by the surrounding medium. They are completely immersed in the feedstock and usually have two or three winged, geometrically optimised propellers. Due to their guiding tubing system, consisting of gibbet, cable winch and lead profile, the stirrers can usually be adjusted to height, tilt and to the side.

Paddle stirrers have a horizontal, vertical or diagonal axis (Figure 7.23 and 7.24). The motor is positioned outside the digester. Junctions, where the shaft passes the digester ceiling, membrane roof or the digester wall, have to be tight.

Another possibility for mechanical mixing is axial stirrers. They are often operated continuously. Axial stirrers are usually mounted on shafts that are centrally installed on the digester ceiling. The speed of the engine, which is placed outside of the digester, is reduced to several revolutions per minute, using a transmission. They should create a steady stream in the digester that flows from the bottom, up to the walls.

In horizontal digesters, the slow running paddle-reel stirrers are usually used, but they can also be installed in vertical digesters. Paddles are fixed on the horizontal stirring axis, which is mixing and pressing forward (plug-flow) the feedstock. The stirring effect should only provide vertical mixing of the feedstock. The horizontal plug-flow stream is assured by the insertion of fresh feedstock into the digester. Heating tubes for heating the feedstock are often integrated in the drive shaft and in the stirrer arms. Paddle- or reel stirrers run several times per day, with short sequences and low speed.

7.7.2 Pneumatic stirring

Pneumatic stirring uses the produced biogas, which is blown from the bottom of the digester through the mass of the feedstock. The bubbles of rising gas cause a vertical movement and stir the feedstock. This system has the advantage that the necessary equipment is placed outside the digester (pumps and compressors), so the wear is lower. Pneumatic stirring not frequently used in agricultural biogas plants, as the technology is not appropriate for destruction of floating layers. Pneumatic stirring can only be used for thin liquid feedstock, with low tendency of forming floating layers.

7.7.3 Hydraulic stirring

If stirred hydraulically, the feedstock is pressed by pumps and, horizontal or additional vertical pivoted vents, in the digester. The suction and discharging of the feedstock must be designed in such a way that the digester content is stirred as thoroughly as possible. Hydraulically stirred systems have the advantage that the mechanical parts of the stirrers are placed outside the digester, subject to lower wear and can be easily maintained. Hydraulic mixing is only occasionally appropriate for destruction of floating layers and, like the pneumatic stirring, only used for thin liquid feedstock, with low tendency of forming floating layers.

7.8 Biogas storage

Biogas production must be maintained as stable and constant as possible. Inside the digester, biogas is formed in fluctuating quantities and with performance peaks. When biogas is utilised in e.g. a CHP unit, the demand for biogas can vary during the day. To compensate for all these variation, it is necessary to temporarily store the produced biogas, in appropriate storage facilities.

Various types of biogas storage facilities are available today. The simplest solution is the biogas storage established on top of digesters, using a gas tight membrane, which has also the function of digester cover. For larger biogas plants, separate biogas storage facilities are established, either as stand-alone facility or included in storage buildings. The biogas storage facilities can be operated at low, medium or high pressure.

Correct selection and dimensioning of biogas storage facility brings substantial contribution to the efficiency, reliability and safety of the biogas plant while ensuring constant supply of biogas and minimising biogas losses.

All biogas storage facilities must be gas tight and pressure-resistant, and in case of storage facilities which are not protected by buildings, they must be UV-, temperature- and weather proof. Before starting-up the biogas plant, the gas storage tanks must be checked for gas tightness. For safety reasons, they must be equipped with safety valves (under-pressure and over-pressure) (Figure 7.25) to prevent damages and safety risks. Explosion protection must also be guaranteed and an emergency flare is required. The gas storage facility must have the minimum capacity corresponding to one fourth of the daily biogas production. Normally, a capacity of one or two days gas production is recommended.

Figure 7.25 Safety pressure facilities and valves (AGRINZ 2006)

7.8.1 Low pressure tanks

The frequently used low pressure tanks have an overpressure range of 0,05 to 0,5 mbar and are made of special membranes, which must meet a number of safety requirements. The membrane tanks are installed as external gas reservoirs or as gas domes/covers, in top of the digester.

External low-pressure reservoirs can be designed in the shape of membrane cushions/ gas balones (Figure 7.26). The membrane cushions are placed in buildings for weather protection or equipped with a second membrane.

If the digester or the post-digester is used for biogas storage, both must be covered with gas tight membrane domes (double membrane reservoirs) as shown in Figure 7.27 *left*, fixed on the upper edge of the digester. A supporting frame can be installed in the digester to hold the membrane when it is empty. The membrane expands according to the volume of gas contained. In order to limit the membrane expansion, a special net can be mounted over it (Figure 7.27 *right*).

Figure 7.26 External low pressure gas storage tanks (RUTZ 2007)

Figure 7.27 Digester cover of gas tight membrane, seen from the inside of the tank -*left* (AGRINZ 2006); Digester cover of gas tight membrane, outfitted in exterior with expansion net -*right* (RUTZ 2006)

7.8.2 Medium and high pressure biogas storage

Biogas can also be stored in medium and high pressure reservoirs, at pressures between 5 and 250 bar, in steel pressure tanks and bottles. These kinds of storage types have high operation costs and high energy consumption. For gas reservoirs up to 10 bar, energy requirements of up to 0,22 kWh/m³ must be considered and for high pressure reservoirs with 200 to 300 bar, the energy requirement is of about 0,31 kWh/m³. Because of their high costs, these kinds of biogas storage are rarely used in agricultural biogas plants.

7.8.3 Biogas flares

There are situations where more biogas is produced than it can be used for energy generation. This can happen due to extraordinary high gas production rates or through breakdown/maintenance of the energy recovery system. In such cases, back-up solutions are necessary, such as additional biogas storage or additional energy production systems. Storage of biogas is possible for short periods without compression, but for periods of more than a few hours it is generally not feasible due to the large volume. The additional energy production unit (i.e. a second CHP plant) is not economically feasible. For this reason, each biogas plant is equipped with a biogas flare. In situations where there is an excess of biogas, which cannot be stored or used, flaring is the ultimate solution, necessary to eliminate any safety risks and to protect the environment. In exceptional situations, flaring could be the solution for safe disposal of the biogas produced by AD processes, where energy recovery is not feasible.

The combustion process determines the benefits of one flare type over another. Flaring of biogas is regulated through emission standards and performance criteria for the used flares. Two parameters, temperature and residence time, form the performance specification for most advanced flares. The design of flares aims to maximise the conversion of methane and thus to minimise the release of unburned methane and of any other products of incomplete oxidation (e.g. carbon monoxide). Several unwanted by-products of biogas combustion may be formed, depending on the ratio of air, temperature and on the kinetics of the combustion reactions. In order to optimise the flaring process, the temperature range must be kept between 850-1200^{o}C and the residence time of minimum 0,3 seconds.

Irrespective of the type of flare, safe and reliable operation of a flare requires a number of features, in addition to burner and enclosure. Essential safety features include a flame-arrestor, failsafe valve and ignition system, incorporating a flame detector. A gas blower is also essential, to raise the pressure of the gas to 3-15 kPa at the burner. The necessity of gas cleaning or conditioning depends on the biogas quality and whether the gas is used in an energy recovery plant, where there is lower tolerance for entrained particulates and for a number of acidic gases formed during combustion. There are two basic types of biogas flares: open flares and enclosed flares.

An *open flare* is essentially a burner, with a small windshield to protect the flame. Gas control is rudimentary - in many cases, a coarse manual valve. The rich gas mixture, lack of insulation and poor mixing lead to an incomplete combustion and a luminous flame, which is often seen above the windshield. Radiant heat loss is considerable and this leads to cool areas at the edge of the flame and quenching of combustion reactions to yield many undesirable by- products.

Historically, open flares have been popular in the past, because of their simplicity and low cost and because of permissive or absent legislation and control regarding emissions standards. Henceforward, strict regulation and emission control is likely to limit their use.

Enclosed flares are usually ground based, permanent plants, housing a single or several burners, enclosed within a cylindrical enclosure, lined with refractory material. Designed for purpose, the enclosure prevents quenching and, as a result, the combustion is much more uniform and the emissions are low. Monitoring emissions is relatively easy and basic continuous monitoring of temperature, hydrocarbons and carbon monoxide maybe incorporated, as means of process control. Increased engineering and process control provide greater turn down flexibility (the ratio of minimum biogas flow to maximum biogas flow under which satisfactory operating conditions are maintained). Manufacturers typically quote turndown of 4-5:1 for biogas quality of 20-60% methane (by volume). Higher turndown of up to 10:1 is achievable, but on the expense of combustion quality, as the heat release does not enable adequate temperatures to be achieved.

Figure 7.28 Modern biogas flares (RUTZ 2007)

7.9 Biogas cleaning

7.9.1 Gas conditioning

When biogas leaves the digester, it is saturated with water vapours and contains, in addition to methane (CH_4) and carbon dioxide (CO_2), various amounts of hydrogen sulphide (H_2S). Hydrogen sulphide is a toxic gas, with a specific, unpleasant odour, similar to rotten eggs, forming sulphuric acid in combination with the water vapours in biogas. The sulphuric acid is corrosive and can cause damage to the CHP engines, gas pipelines, exhaust pipes etc. To prevent this, biogas must be desulphurizated (removal of H_2S) and dried.

The manufacturers of CHP units have minimum requirements for the properties of the combustible gas (Table 7.2). The combustion properties must be guaranteed, to prevent damage to the engines. This also applies to the use of biogas. For other utilisations of biogas (e.g. as vehicle fuel or in fuel cells), further gas up-grading and conditioning measures are necessary.

Table 7.2 Minimum properties for combustible gases with relative oxygen content of 5 %

Heat value (lower heat value)	**H_u**	**$\geq$ 4 kWh/m^3**
Sulphur content (total)	S	$\leq$ 2,2 g/m^3 CH_4
or H_2S-content	H_2S	$\leq$ 0,15 Vol.- %
Chlorine content (total)	Cl	$\leq$ 100,0 mg/m^3 CH_4
Fluoride content (total)	F	$\leq$ 50,0 mg/m^3 CH_4
Sum of Chlorine and Fluoride	(Cl + F)	$\leq$ 100,0 mg/m^3 CH_4
Dust (3 ... 10 μm)		$\leq$ 10,0 mg/m^3 CH_4
Relative humidity (at lowest intake air temperature, i.e. condensation in intake pipe and gas control path	φ	< 90 %
Flow pressure before entry into the gas control path	p_{Gas}	20 ... 100 mbar
Gas pressure fluctuation		< ± 10 % of set value
Gas temperature	T	10 ... 50 °C
Hydrocarbons (> C5)		< 0,4 mg/m^3 CH_4
Silicon (at Si > 5 mg/m^3 CH_4 oil analysis of metal content < 15 mg/kg oil observed)	Si	< 10,0 mg/m^3 CH_4
Methane e count (Biogas MC approx. 135)	MZ	> 135

7.9.2 Desulphurization

Dry biogas from AD of animal manure has an average content of 1 000 – 3 000 ppm H_2S (AGELIDAKI, 2003). The biogas produced by co-digestion of animal manure with other substrates can contain various levels of H_2S. Most of the conventional engines used for CHP generation need biogas with levels of H_2S below 700 ppm, in order to avoid excessive corrosion and rapid and expensive deterioration of lubrication oil.

Removal of H_2S from biogas (desulphurisation) can be done by various methods, either biological or chemical, taking place inside or outside the digester. Desulphurisation depends on the content of H_2S and the throughput rate throughout the desulphurization equipment. The throughput rate can fluctuate significantly, depending on the process. Higher biogas production and thus high throughput rates can be observed after insertion of new feedstock into the digester and during stirring. Throughput rates up to 50% higher than normal can occur for short time intervals. For this reason and in order to ensure complete desulphurization, it is necessary to use over-dimensioned desulphurization equipment, compared to average throughput rate.

Biological desulphurization inside the digester

Biological oxidation is one of the most used methods of desulphurisation, based on injection of a small amount of air (2-8 %) into the raw biogas. This way, the hydrogen sulphide is biologically oxidised either to solid free sulphur (Figure 7.29) solid) or to liquid sulphurous acid (H_2SO_3):

$$2H_2S + O_2 \rightarrow 2H_2O + 2S$$
$$2H_2S + 3O_2 \rightarrow 2H_2SO_3$$

In practice, the produced sulphur precipitate is collected and added to the storage tanks where it is mixed with digestate, in order to improve fertiliser properties of digestate. Biological desulphurization is frequently carried out inside the digester, as a cost-effective method. For this kind of desulphurization, oxygen and *Sulfobacter oxydans* bacteria must be present, to convert hydrogen sulphide into elementary sulphur, in the presence of oxygen. *Sulfobacter oxydans* is present inside the digester (does not have to be added) as the AD substrate contains the necessary nutrients for their metabolism. The oxygen is provided by injection of air in the top of the digester, done with the help of a very small compressor. The air injection pipes inside the digester should be positioned on the opposite side of the biogas output, in order to avoid blockage of the output pipe.

Figure 7.29 Elementary sulphur, resulted from biological desulphurization inside the digester (RUTZ 2007)

The air is injected directly in the headspace of the digester and the reactions occur in the reactor headspace, on the floating layer (if existing) and on reactor walls. Due to the acidic nature of the products there is the risk of corrosion. The process is dependent of the existence of a stable floating layer inside the digester. For these reasons, the process is often taking place in a separate reactor as shown in figure 7.30.

Biological desulphurization outside the digester

Biological desulphurization can take place outside the digester in desulphurization tanks or desulphurization columns. This method facilitates the control of desulphurization process and the precise adjustment of oxygen addition.

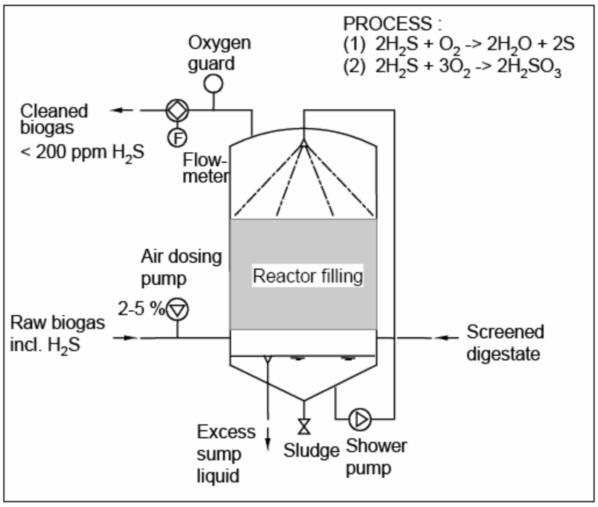

Figure 7.30 Schematic diagram of system for biological H_2S oxidation (ANGELIDAKI 2004)

The reactor (figure 7.31) is similar to a scrubber, consisting of a porous filling (randomly packed plastic elements or similar) where microorganisms can grow, a sump, a pump and nozzle arrangement, allowing regular showering of the filling. The reactor shown in figure 7.31 has a capacity of 80 m^3 with 50 m^3 filling material. The H_2S is oxidized through a biological process to acidic products or free sulphur, by upstream injection of a small amount of atmospheric air.

Figure 7.31 Reactor tank for removal of hydrogen sulphide (ANGELIDAKI 2004)

Showering has the function of washing out acidic products and supplying nutrients to the microorganisms. The sump must therefore contain a liquid with high alkalinity, rich in essential nutrients for the microorganisms. Digestate, preferably screened, is in this case the ideal and available choice.

A reactor loading of approx. 10 m^3/h of biogas per m^3 of reactor filling and a process temperature around 35°C can normally be chosen. The process has proven very efficient, provided sufficient air is injected (slightly more than stoichiometrically needed). The sump pH must be maintained at 6,0 ppm or higher. A washing procedure, where the filling elements are showered through with an air/water mixture, has to be carried out at regular intervals in order to prevent free sulphur deposits from closing the reactor filling.

In some cases, when biogas is stored or passing a digestate storage take H_2S reactor is omitted and only air is injected. Biogas cleaning is, in such case, relying on the formation of a floating layer in the storage tank, on which the microorganisms can grow and perform the oxidation. A floating layer can usually be maintained with the choice of a low mixing intensity, without too many problems in operating the tank as buffer storage. This solution is more cost effective, but more unreliable as well, as floating layers are rather unstable, i.e. sinking overnight without notice and resurfacing some days later. Periods with low efficiency of H_2S removal are therefore likely to occur.

Chemical desulphurization inside the digester

Desulphurisation can also be done by adding a chemical substance to the feedstock mixture, inside the digester. This way, the sulphur is chemically bounded during the AD process, preventing the release of hydrogen sulphide into biogas. Thereby, sulphur is not lost, but remains in the digestate.

Chemical desulphurization outside the digesters

Chemical biogas desulphurisation can take place outside of digester, using e.g. a base (usually sodium hydroxide). The method needs special equipment.

Another chemical method to reduce the content of hydrogen sulphide is to add commercial ferrous solution to the feedstock. Ferrous compounds bind sulphur in an insoluble compound in the liquid phase, preventing the production of gaseous hydrogen sulphide. The method is rather expensive, as the consumption of ferrous material on a stoichiometric basis has proven to be 2-3 times the desired reduction in gaseous hydrogen sulphide (ANGELIDAKI 2004). A cheaper alternative is thus to supply co-substrates (organic wastes) containing ferrous materials and to use the ferrous addition only as a back up.

7.9.3 Drying

The relative humidity of biogas inside the digester is 100%, so the gas is saturated with water vapours. To protect the energy conversion equipment from wear and from eventual damage, water must be removed from the produced biogas.

The quantity of water contained by biogas depends on temperature. A part of the water vapours can be condensed by cooling of the gas. This is frequently done in the gas pipelines transporting biogas from digester to CHP unit. The water condensates on the walls of the sloping pipes and can be collected in a condensation separator, at the lowest point of the pipeline. A prerequisite for effective biogas cooling in the pipelines is a sufficient length of the respective pipes. If the gas pipelines are placed underground, the cooling effect is even higher. For underground pipes, it is very important to be placed on a stable foundation, in order to guarantee the incline of the pipes, which can be affected by sinking or moving ground. The condensation separator must be kept frost free and easily accessible, in order to be regularly emptied. In addition to the removed water vapours, condensation also removes some of the undesirable substances such as water soluble gases and aerosols.

Another possibility of biogas drying is by cooling the gas in electrically powered gas coolers, at temperatures below 10°C, which allows a lot of humidity to be removed. In order to minimize the relative humidity, but not the absolute humidity, the gas can be warmed up again after cooling, in order to prevent condensation along the gas pipelines.

7.10 Digestate storage

The digested substrate is pumped out of the digester through pumping sequences and transported through pipelines to storage facilities, in the vicinity of the digester, where digestate can be temporarily stored (several days).

When used as fertiliser, digestate is transported away from the biogas plant, through pipelines or with special vacuum tankers, and temporarily stored in storage tanks placed e.g. out in the fields, where the digestate is applied. The total capacity of these facilities must be enough to store the production of digestate for several months. Agricultural legislations, in many European countries, require six to nine months storage capacity for animal manure, slurry and digestate, in order to ensure their optimal and efficient utilisation as fertiliser and to avoid application during winter season.

Digestate can be stored in concrete tanks or in lagoon ponds, covered by natural or artificial floating layers or by membrane covers.

Figure 7.32 Storage tanks covered with natural floating layer (DANISH BIOGAS ASSOCIATION 2008)

Figure 7.33 Membrane covered storage tanks (DANISH BIOGAS ASSOCIATION 2008)

Figure 7.34 Open pond lagoons for digestate storage (AGRINZ 2006)

Losses of methane and nutrients from storing and handling of digestate are possible. Up to 20% of the total biogas production can take place outside the digester, in storage tanks for digestate. In order to prevent methane emissions and to collect the extra gas production, storage tanks should always be covered with a gastight membrane for gas recovery. Modern biogas plants have the storage tanks for digestate sealed with a gas-tight membrane.
When digestate is temporarily stored in storage facilities out in the fields, these should also be, as a minimum, covered with a natural floating layer, in order to reduce the risk of

ammonia volatilisation. Experience shows that establishment of artificial floating layers on storage tanks for digestate, can reduce ammonia volatilization from 20% to less than 2% (Figure 7.35).

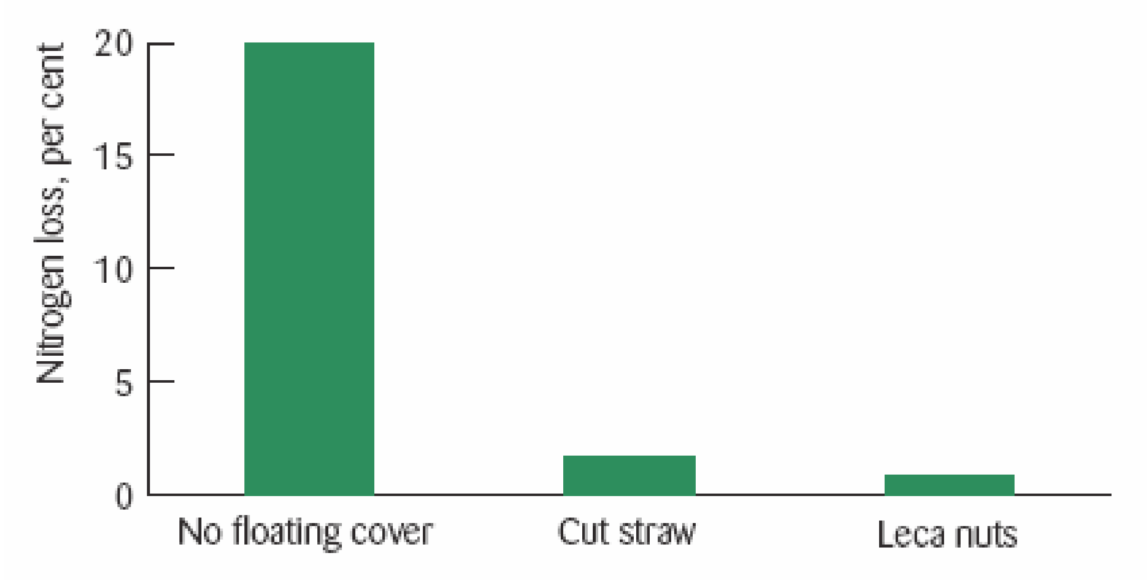

Figure 7.35 Floating cover on digestate storage tanks reduces ammonia volatilization. (BIRKMOSE 2002)

7.11 The control unit

A biogas plant is a complex installation with close interrelationships between all parts. For this reason, centrally computerised monitoring and controlling is an essential part of the overall plant operation, aiming to guarantee success and avoid failures (Figure 7.36 and 7.37). Standardization and further development of the AD process technologies is only possible with regular monitoring and documentation of important data. Monitoring and documentation is also necessary for process stability, in order to be able to recognize deviations from standard values and to make possible early intervention and corresponding corrective measures.

The *monitoring process* includes the collection and analysis of chemical and physical parameters. Regular laboratory tests are required to optimize the biochemical process and to avoid inhibition or collapse of biogas production. Following parameters should be monitored, as a minimum:

- Type and quantity of inserted feedstock (daily)
- Process temperature (daily)
- pH value (daily)
- Gas quantity and composition (daily)
- Short-chain fatty acids content
- Filling level

The monitoring process should be assisted by the plant manufacturer, as included in the service agreement which must follow the construction phase of the biogas plant.

The *control of biogas plants* is increasingly automated through use of specific computer based process control systems. Even wireless remote controlling is possible. The automated control of the following components is state of the art:

- Feedstock feeding
- Sanitation
- Digester heating
- Stirring intensity and frequency
- Sediment removal
- Feedstock transport through the plant
- Solids-liquids separation
- Desulphurization
- Electric and heat output

The type of controlling and monitoring equipment varies from simple timers up to the visualization of computer-supported controlling with a remote alarm system. However, in practice, the measurement and technical control equipment of agricultural biogas plants are often very simple due to economic reasons.

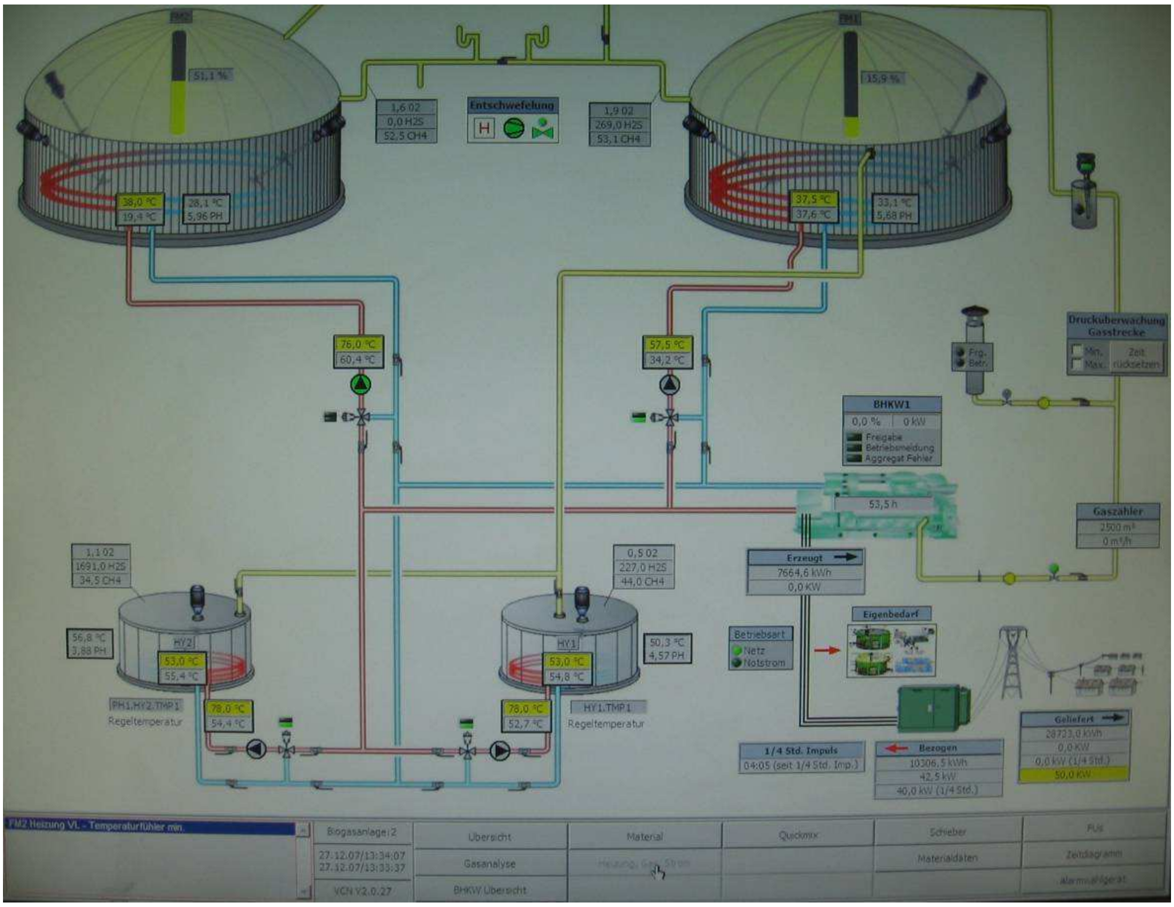

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Figure 7.36 Screenshot of a computer based monitoring plan for an agricultural biogas plant with two main digesters (AGRINZ 2006)

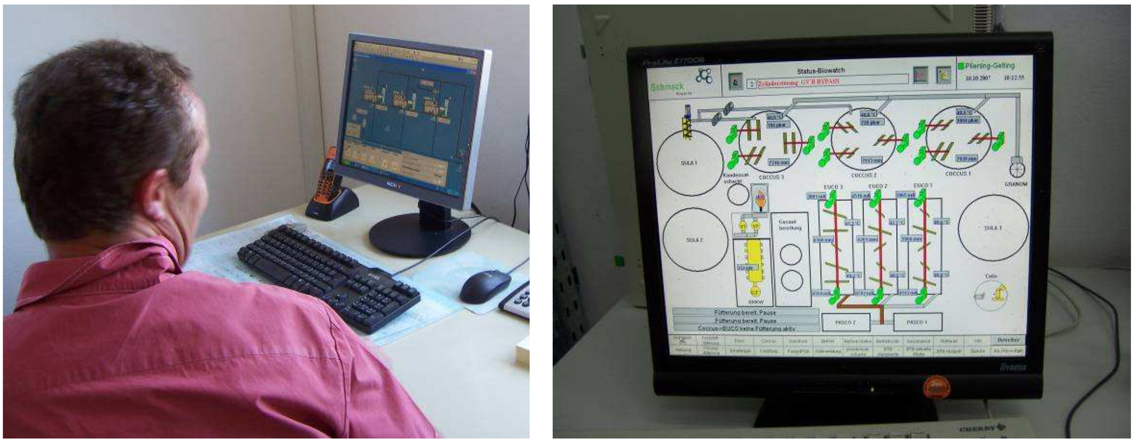

Figure 7.37 Computer based controlling systems (RUTZ 2007)

7.11.1 Quantity of pumpable feedstock input

The quantity of pumpable feedstock inserted in the digester can be determined using flow measurement instruments called flow-meters. The flow-meters must be robust and should not be sensible if they become dirty. Currently, inductive and capacitive flow meters are used, but also instruments using ultrasound and thermal conductivity measurements are increasingly used. Flow- meters which have mechanical parts are less suitable for biogas plants.

For the determination of solid feedstock input like maize silage, appropriate weighting equipment is used which allows adjusting the dosage of solids.

7.11.2 Digester filling level

Monitoring of the filling level in digesters and in storage containers is done using ultrasound or radar techniques, which measure the hydrostatic pressure on the floor of the digester or the distance to the surface of the liquid.

7.11.3 Filling level of the gas reservoirs

Measuring the filling level of gas reservoirs is important (e.g. for operation of CHP plants). If too little biogas is available, the CHP plant will be automatically switched off and restarted when the filling level is beyond the minimum allowed for CHP operation. Measurement of filling level is usually done by pressure sensors.

7.11.4 Process temperature

The temperature inside the digester must be constant and is therefore permanently monitored. There are several measuring points inside the digester for temperature monitoring of the whole process. The measured values are sent to a computer based data logger and can be visualized. This data input also enables automatic control of the heating cycle.

7.11.5 pH-value

The pH-value of the substrate provides important information about the performance of the AD process. Measurement of pH is done on representative sample from the digester content, which is taken at regular intervals. The pH is measured manually, using ordinary pH-meters, available on the market.

7.11.6 Determination of volatile fatty acids (VFA)

The monitoring of VFA facilitates evaluation and optimisation of the AD process. The measurements concern the spectrum and the concentration of short-chain fatty acids. Continuous measurement is difficult to carry on site, due to difficulty of analysis methods. A correct evaluation of the actual process biology is difficult even in laboratory, due to the time passing between taking the sample and performing the analysis in the laboratory. Many manufacturers of biogas plants and consulting companies offer VFA analysis within their contracting commitments. As an alternative or in addition to VFA monitoring, the concentration of chemical oxygen demand (COD) can be monitored continuously.

7.11.7 Biogas quantity

The measurement of the biogas quantity is done by instruments with the generic name gas-meters. Measurement of gas production (gas quantity) is an important tool to assess process efficiency. Variations of gas production can indicate process disturbances and require adequate adjustment measures. The gas-meters are usually installed directly in the gas lines. The measured biogas quantities should be recorded for assessing gas production patterns and trends and the overall performance of the biogas plant.

7.11.8 Biogas composition

The composition of biogas can be continuously monitored by gas analysis and the use of appropriate measurement devices. The results can be used for controlling the AD process and for the subsequent processes (e.g. gas cleaning).

Determination of gas composition is done using sensors based on heat decalescence, heat transmission, infrared radiation absorption, chemisorption and electro-chemical sensing. Infrared sensors are suitable for determination of methane and carbon dioxide concentrations. Electro-chemical sensors are used for hydrogen, oxygen and hydrogen sulphide contents.

Measurement of gas composition can be done manually or automatically. The manual measurement devices provide information about the actual gas composition, but the subsequent integration of data in a computerised plant control system is difficult. Therefore, automatically gas composition measurements are preferred.

How to get started

8 Planning and building a biogas plant

This chapter provides guidelines about the layout of a biogas plant and the planning and building process.

8.1 Setting up a biogas plant project

The aim of establishing a biogas plant can vary from environmental protection and waste reduction to renewable energy production, and can include financial and non-financial incentives. Local farmers and farmers organisations, organic waste producers and collectors, municipalities, energy producers and other involved actors are the usual initiators of biogas projects. From the vital spark of a biogas project idea to the end of its life-time, the process undergoes the following steps:

1. Project idea
2. Pre-feasibility study
3. Feasibility study
4. Detailed planning of the biogas plant
5. Permission procedure
6. Construction of the biogas plant
7. Operation and maintenance
8. Re-investment, renewal and replacement of components
9. Demolition or refurbishment

In order to define a concrete biogas project idea, following questions must be answered:

- What is the aim of the biogas project?
- What is the capacity of the investor to realise the project?
- How can continuous and uniform supply of feedstock be secured?
- Where can the biogas plant be located?

The central premises for the implementation of a biogas project are the existence and availability of the feedstock supply. Furthermore, the possibility of selling or using the end products of the biogas plant, namely biogas/ biomethane, electricity, heat and digestate, has to be ensured. The next step is to assess if the project is feasible in local conditions. Thereby the following issues must to be considered:

- Defining and evaluating a business plan and a financing strategy
- Involving an experienced planning company
- Involving, from early stages of the project, other key actors (local authorities, municipalities, feedstock suppliers, financing companies and the general public)

There are different successful models of setting up a biogas project, depending on the availability of the feedstock and the financial capability of the investors.

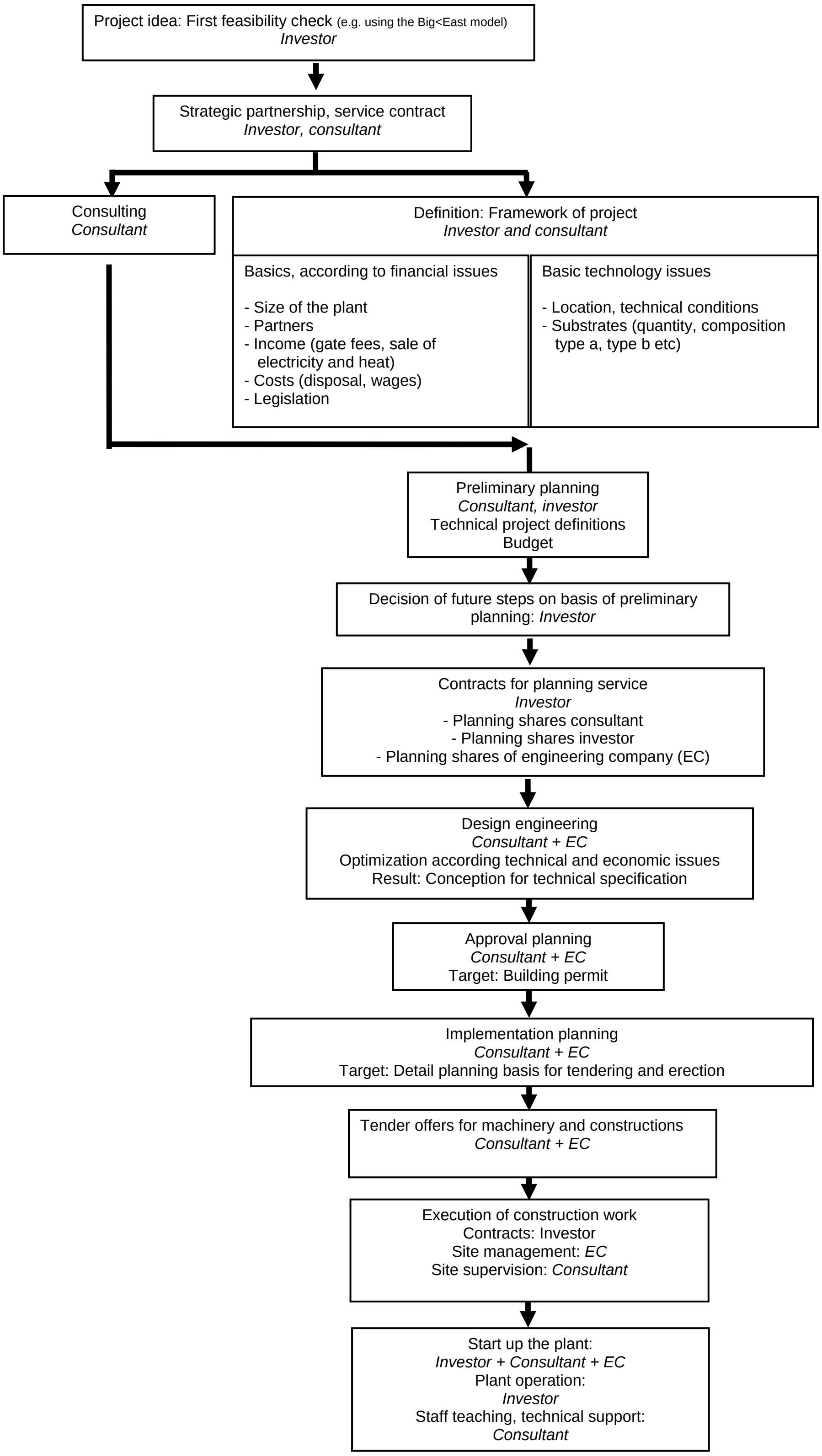

Figure 8.1 Block diagram, showing the main steps of a biogas project.

Each project is individual and needs unique approaches (site specific projects), although some generic steps are similar for all biogas projects (Figure 8.1).
The process starts with the project idea and the first feasibility check (which can be done by using the Big East calculation model in the attached CD). If the project initiator and the investor arrive to the point of making a decision, an experienced biogas consulting company should be involved at this stage. The assistance of an engineering company (e.g. general contractor) could be necessary as well.

In parallel to these project steps, the financing scheme has to be developed. The concrete financial situation determines the steps to be taken. The usual practice is to self-finance the project up to the point of ready made preliminary planning, without any involvement of banks or external financers. If this is not possible, doubts could occur about the project itself or about the reliability of the investor. Anticipating advantages and risks of the investment is also a consideration which has to be made by the investor.

The preliminary planning sum up all boundary conditions (technological aspects and investment budget), which are important for an external financer. A preliminary planning report should be handed out to potential financers. The potential financers could be banks, institutional investors, private persons, groups of private persons, etc. A non disclosure agreement (NDA) is recommended to be signed with those who receive the preliminary planning report.

The financing options depend to a great extent on local conditions and on the situation of the project initiator, so there are no universal guidelines for this. Nevertheless, some further clarifications and general aspects can be found in Chapter 10 of this handbook.

8.2 How to secure continuous feedstock supply

The first step in developing a biogas project idea is to make a critical inventory of the available types and amounts of feedstock in the region. There are two main categories of biomass which can be used as feedstock in a biogas plant. The first category includes farm based products such as animal manure and slurries, energy crops (e.g. maize, grass silage), vegetable residues, agricultural by- products and farm based wastes. The second category consists of a broad range of suitable organic wastes from the food, feed and pharmaceutical industry, catering waste, municipal solid waste etc. The suitability of all feedstock types must be evaluated regarding their methane potential, digestibility, possible contamination with chemical, biological or physical contaminants, as well as from an economic point of view (e.g. gate fees, collection and transportation costs, seasonality).

The amount of available constant feedstock supply and the size of the future biogas plant are closely related when developing a biogas project. The supply costs of a specific feedstock must always be included in the evaluation of its suitability for AD. When negotiating feedstock supply for the future biogas plant, the feedstock characteristics described in subchapters 8.2.1 and 8.2.2 can provide guidance for this process.

8.2.1 Characterising the plant size for farm based feedstock

Animal manure and energy crops are among the most common farm based feedstock types for agricultural biogas plants. Their main characteristics are described in Table 8.1.

Table 8.1 Typical data for a range of farm based feedstock (FINSTERWALDER 2008)

	DM content [%]	oDM content [%]	Biogas yield [m³/t oDM]	Biogas yield [m³/t FF]	Methan content [%]
Cattle manure	10	75	340	25	55
Pig manure	8	75	400	24	58
Grass silage	40	85,6	656	225	55
Maize silage	32	95,4	611	187	53

In order to determine the suitable plant size regarding e.g. the electrical output, it is necessary to consider the available feedstock. The following two examples describe how to easily calculate the suitable installed capacity in kW_{el} output.

Example of determining the plant size/ installed capacity of a biogas plant based on manure:

- **The daily volume of manure (m^3/ day) has to be determined**
- **The content of total solids in manure/ slurry (DM%) has to be specified**

If the DM content of manure/ slurry is 9-10%, the potential electrical power capacity is calculated by multiplying the daily volume of manure by 2,4 kW_{el} d/m^3.

A farmer having 200 milk cows will produce about 10 m^3/ day cow slurry/ manure with a DM of 10%.
The calculation of the electrical power installation will be:

10 m^3/d x 2,4 kWeld/m^3 = 24 kW_{el}

Example of determining the plant size of a biogas plant digesting energy crops:

- **The available area under cultivation (e.g. maize, grass) has to be determined in hectares (ha)**
- **The potential of electrical power per hectare and per year (kW_{el}/ ha/ year) is estimated, based on average soil quality and whether conditions.**

Assuming that every hectare is worth 2,5 kW_{el} electrical power per year, the possible electrical power capacity is calculated by multiplying the available area under cultivation with 2,5 kW_{el}/ ha.

200 ha x 2,5 kW/ha = 500 kW_{el}

Having the results from manure and energy crops, the sum of the results gives the potential electrical power generation of the future biogas plant.

Agricultural biogas plants can benefit from the advantage of scale. Experience from Germany shows that, biogas plants, using energy crops as feedstock, with sizes below 250 kW_{el} need special efforts to be economically viable. If after the first check, the biogas plant size is too small, it may be worth thinking about co-operation with other farmers, to achieve a size which is economically profitable. This situation is very common in Europe, where there are biogas plants owned by several farmers working in co-operation.

8.2.2 Characterising the plant size for industrial/ municipal wastes

In most cases, municipalities and waste collectors need to treat the wastes they collect. Many agricultural biogas plants co-digest industrial organic wastes or source separated organic wastes from municipalities.

When considering supplying these kinds of wastes to a future biogas plant, the first step is to evaluate the feedstock quality and methane potential. The potential plant size can be estimated based on the above mentioned data. The potential gas yield of substrates varies from producer to producer, depending on the technology and the raw materials used (Table 8.2).

Table 8.2 Data for some waste types, frequently used as AD substrates (FINSTERWALDER 2008)

	DM content [%]	oDM content [%]	Biogas yield [m³/t oDM]	Biogas yield [m³/t FF]	Methan content [%]
Food waste	27	92	720	179	65
Biowaste (source separated)	40	80	454	145	60
Grease trap removal (pre-dewatered)	36	69	1 200	298	61

The quality of organic wastes varies from country to country and from region to region, being dependent of local consumer's habits. It is not likely that even an expert will be able to estimate biogas yields of wastes by visual examination only. After having checked the availability of a certain type of waste, it is necessary to do eudiometer[1] testing of gas yield and gas quality, for appropriate dimensioning of the future biogas plant.

8.2.3 Feedstock supply schemes

Successful planning of a biogas project implies elaboration of feedstock supply schemes. There are supply schemes for a single supplier or for several suppliers.

1. A *single supplier* (e.g. farm, organic waste producer) has enough manure, organic waste, agricultural land or all of the above, to provide the feedstock necessary to run a biogas plant.
2. *Several suppliers* (e.g. smaller farms, organic waste producers) work together in a consortium (e.g. in a cooperative company, limited company etc.) to build, run and supply feedstock to a biogas plant.

In both cases, it is important to secure constant and long term supply of the necessary AD feedstock. This is rather simple if the supplier is a single farm, with corresponding own cultivated area. In the case of a consortium of owners and feedstock suppliers, every supplier has to sign a long term contract, stipulating the following as a minimum:

- Contract duration
- Guaranteed amount of feedstock supply or area of cultivation
- Guaranteed quality of the delivered biomass
- Payments conditioned by the delivered quantity and quality

In the situation where the feedstock suppliers are also investors or co-owners of the biogas plant, a separate contract has to be negotiated with each one of them, stipulating their duties and responsibilities.

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[1] Eudiometer = a laboratory glassware that measures the change in volume of a gas mixture, following a chemical reaction. It is used to analyze gases and to determine the differences in chemical reactions.

8.3 Where to locate the biogas plant

The next planning step in a biogas project idea is to find a suitable site for the establishment of the plant. The list below shows some important considerations to be made, before choosing the location of the future plant:

- The site should be located at suitable distance from residential areas in order to avoid inconveniences, nuisance and thereby conflicts related to odours and increased traffic to and from the biogas plant.
- The direction of the dominating winds must be considered in order to avoid wind born odours reaching residential areas.
- The site should have easy access to infrastructure such as to the electricity grid, in order to facilitate the sale of electricity and to the transport roads in order to facilitate transport of feedstock and digestate.
- The soil of the site should be investigated before starting the construction.
- The chosen site should not be located in a potential flood affected area.
- The site should be located relatively close (central) to the agricultural feedstock production (manure, slurry, energy crops) aiming to minimise distances, time and costs of feedstock transportation.
- For cost efficiency reasons, the biogas plant should be located as close as possible to potential users of the produced heat. Alternatively, other potential heat users such as heat demanding industry, greenhouses etc. can be brought closer to the biogas plant site.
- The size of the site must be suitable for the activities performed and for the amount of biomass supplied.

The required site space for a biogas plant cannot be estimated in a simple way. Experience shows that e.g. a biogas plant of 500 kW_{el} needs an area of approximate 8 000 m^2. This figure can be used as a guiding value only, as the actual area also depends on the chosen technology.

The following example illustrates a rough estimation of the size of a biogas plant using energy crops as feedstock substrate. The calculation below determines the size of the silo (bunker silo), needed to store the feedstock.

$$AS = MS / (DF * HS)$$

MS: **Mass of feedstock stored in the silo** **[t]**
DF: **Density of feedstock in the silo [t/m^3]**
HS: **Height of silo** **[m]**
AS: **Area of silo** **[m^2]**

The calculation is valid in the case of silos with filling heights of about three meters. The planned biogas plant capacity of 250-750 kW_{el} is used here as an example. The size of the area needed for a specific biogas project will always be the result of detail planning calculations. In the first estimation, a biogas plant needs the double area of the silo. This means:

AB = 2 * AS

AB: Area of biogas plant
AS: Area of silo

8.4 Getting the permits

The procedure, criteria and documentation needed in order to get the permission to build a biogas plant is different from country to country.

In order to get the building permit, the investor must document the compliance of the project with national legislation concerning issues like handling and recycling of manure and organic wastes, limit values for emissions, exhaust emissions, noise and odours, impact on groundwater, protection of landscape, work safety, buildings safety etc.

Experience shows that it is very important to involve local authorities in an early stage of the project, to provide them first hand information and to require help with the permitting process and the implementation of the project.

Involving an experienced planning company in getting the building permit can be useful or necessary, depending on the local situation. Some building companies are willing to do this work for low prices, hoping to get the building contract.

8.5 Start up of a biogas plant

The construction of a biogas plant is similar to construction work in any other business field, but starting up the biogas plant is an operation which must be conducted by experienced people, who are familiar with the design of the plant and with the microbiology of the AD process.

Starting up a biogas plant should always be done by the company who designed and built the plant. During the start up, the plant manager and the staff, who are in charge and responsible for the future plant operation, are trained in running and maintaining the biogas plant. The way this work is done, differs from case to case.

Before starting up the biogas plant, the plant owner must check if all the obligations included in the building permission are fulfilled. The next step is to fill up the digesters with manure or with digestate from a well functioning biogas plant, with the aim of inoculating the new digester with populations of micro-organisms necessary for the AD process. Before starting to feed the system, the feedstock must be heated up to process temperature.

For a single farm based biogas plant, with up to 500 kW_{el} electrical power capacity, the operating and maintenance time is usually around four hours per day. In case of waste treatment plants, the time dedicated to such activities is negotiated between plant designer and customer.

9 Safety of biogas plants

Construction and operation of a biogas plant is related to a number of important safety issues, potential risks and hazards for humans, animals and the environment. Taking proper precautions and safety measures have the aim of avoiding any risks and hazardous situations, and contribute to ensuring a safe operation of the plant. Fulfilment of important safety issues and stipulating clear preventive and damage control measures is a condition for obtaining the building permit:

- Explosion prevention
- Fire prevention
- Mechanical dangers
- Sound statically construction
- Electrical safety
- Lightning protection
- Thermal safety
- Noise emissions protection
- Asphyxiation, poisoning prevention
- Hygienic and veterinary safety
- Avoidance of air polluting emissions
- Prevention of ground and surface water leakages
- Avoidance of pollutants release during waste disposal
- Flooding safety

9.1 Fire and explosion prevention

Under certain conditions, biogas in combination with air can form an explosive gas mixture. The risk of fire and explosion is particularly high close to digesters and gas reservoirs. Therefore, specific safety measures must be guaranteed during construction and operation of biogas plants. Table 9.1 and 9.2 compare biogas and its main components with other gases, in respect to explosion liability. In both tables, the average biogas composition is: Methane 60 Vol. %, Carbon dioxide 38 Vol. % and other gases 2 Vol. %).

Table 9.1 Properties of gases (FNR 2006)

	Unit	**Biogas**	**Natural gas**	**Propane**	**Methane**	**Hydrogen**
Heat value	kWh/m³	6	10	26	10	3
Density	kg/m³	1,2	0,7	2,01	0,72	0,09
Density ratio gas to air		0,9	0,54	1,51	0,55	0,07
Ignition temperature	°C	700	650	470	600	585
Explosion range	Vol.-%	6 – 12	4,4 – 15	1,7 - 10,9	4,4 - 16,5	4 - 77

Table 9.2 Properties of biogas components; TLV = Threshold Limit Value[2] (FNR 2006)

	Unit	CH_4	CO_2	H_2S	CO	H
Density	kg/m³	0,72	1,85	1,44	1,57	0,084
Density ratio biogas to air		0,55	1,53	1,19	0,97	0,07
Ignition temperature	°C	600	-	270	605	585
Explosion range	Vol.-%	4,4 – 16,5	-	4,3 - 45,5	10,9 - 75,6	4 - 77
TLV-value	ppm	no value	5 000	10	30	no value

In Europe, explosion safety measures are stipulated in the European Directive 1999/92/EC, and explosion hazardous places are classified in terms of zones, based on frequency and duration of the occurrence of an explosive atmosphere.

Zone 0
A place in which an explosive atmosphere, consisting of a mixture of air with flammable substances (gas, vapour or mist), is present continuously, for long periods or frequently. These zones usually do not occur on biogas plant sites.

Zone 1
A place in which an explosive atmosphere, consisting of a mixture of air and flammable substances (gas, vapour or mist), is likely to occur occasionally, in normal operation conditions.

Zone 2
A place in which an explosive atmosphere, consisting of a mixture of air and flammable substances (gas, vapour or mist), is not likely to occur in normal operation conditions, but if it does occur, it will be for a short period only.

Although, in the case of biogas plants, explosions only occur under certain conditions, there is always the risk of fire in case of open flames, circuit sparking of electrical devices or lightning strikes.

9.2 Poisoning and asphyxiation risks

If biogas is inhaled in sufficiently high concentration, it can result in poisoning or asphyxiation symptoms and even death. Especially the presence of hydrogen sulphide (H_2S) in non-desulphurised biogas can be extremely toxic, even in low concentrations.

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[2] The Threshold Limit Value (TLV) of a chemical substance is a level to which it is believed a worker can be exposed day after day for a working lifetime without adverse health effects.

Table 9.3 Toxic effect of hydrogen sulphide (FNR 2006)

Concentration (in the air)	**Effect**
0,03 – 0,15 ppm	Threshold of perception (smell of rotten eggs)
15 – 75 ppm	Irritation of eyes and airways, sickness, vomiting, headaches, absence
150 – 300 ppm (0,015 – 0,03 %)	Paralysis of olfactory nerves
> 375 ppm (0,038 %)	Death through poisoning (after several hours)
> 750 ppm (0,075 %)	Absence and death through respiratory arrest within 30 to 60 minutes
from 1000 ppm (0,1 %)	Fast death through respiratory paralysis within a few minutes

In closed rooms, with low elevation (e.g. cellars, underground rooms etc.) asphyxiation may be caused by the displacement of oxygen by biogas. Biogas is lighter than air, with a relative density of approx. 1,2 kg per Nm^3, but it has a tendency to separate into its compounds. Carbon dioxide, which is heavier, ($D = 1{,}85\ kg/m^3$) sinks to lower areas while methane, which is lighter, ($D = 0{,}72\ kg/m^3$) rises to the atmosphere. For these reasons, in closed spaces, precautions must be taken in order to provide sufficient ventilation. Furthermore, safety equipment must be worn (e.g. gas warning devices, breathing protection etc.) during work in potentially dangerous areas.

9.3 Other risks

Apart from poisoning and asphyxiation, there are other potential dangers related to the activity on a biogas production site (see below). In order to avoid these types of accidents, clear warnings must be placed on the respective parts of the plant and the operating personnel must be trained.

- Other potential sources of accidents include danger of falling from ladders or uncovered areas (e.g. feed funnels, maintenance shafts) or to be injured by movable parts of the plant (e.g. stirrers).

- Equipment like stirrers, pumps, feeding equipment is operated with high electrical voltage. Improper operation or defects of the CHP unit can result in fatal electric shocks.

- Risks of skin burning through unprotected contact with the heating or cooling systems of the biogas plant (e.g. motor coolers, digester heating, heat pumps) must be considered. This also applies to parts of the CHP unit and to the gas flare.

9.4 Sanitation, pathogen control and veterinary aspects

9.4.1 Hygienic aspects of biogas plants

Wastes of animal and human origin, used as AD feedstock, contain various pathogenic bacteria, parasites and viruses. Pathogenic species that are regularly present in animal manures, slurries and household waste are bacteria (e.g. *Salmonellae*, *Enterobacter*, *Clostridiae*, *Listeria*), parasites (e.g. *Ascaris*, *Trichostrangylidae*, *Coccidae*), viruses and fungi. Co-digestion of abattoir and fish-processing wastes, sewage sludge and biowaste increases the diversity of pathogens that are likely to be land-spread and could enter the animal and human food chains.

Utilisation of digestate as fertiliser means application on the fields of several individual farms, with the risk of spreading pathogens from a farm to another.

Biogas production from co-digestion of animal manure and biogenic wastes as well as biogas and digestate utilisation ***may not result*** in new routes of pathogen and disease transmission between animals, humans and the environment. This can be prevented by implementing standardised veterinary safety measures.

Effective control of pathogens can be done through applying the sanitary measures listed below:

- **Livestock health control**. No animal manure and slurries should be supplied from any livestock with health problems.
- **Feedstock control**. Biomass types with high risk of pathogen contamination must be excluded from AD.
- **Separate pre-sanitation** of specific feedstock categories is mandatory, as stipulated by European Regulation EC 1774/2002[3]. Depending on the category of feedstock, the regulation requires either pasteurization (at 70°C for one hour), or pressure sterilization (at minimum 133°C for at least 20 minutes and absolute steam pressure of minimum 3 bar).
- **Controlled sanitation.** In the case of feedstock categories which, according to EC Regulation 1774/2002, do not require separate pre-sanitation, the combination of AD process temperature and a minimum guaranteed retention time (MGRT) will provide effective pathogen reduction/ inactivation in digestate.
- **Control of pathogen reduction efficiency** in digestate by using indicator organisms. The efficiency of pathogen reduction must not be assumed, but verified by using one of the accredited indicator organism methods (See chapter 9.4.3).

9.4.2 Parameters for hygienic performance of biogas plants

Effective pathogen reduction in digestate is provided by implementation of a separate pre-sanitation process, for the feedstock types which require special sanitation (e.g. waste waters from slaughter houses, food and catering wastes, flotation sludge). For feedstock types which do not require separate sanitation (animal manure and slurries, energy crops, vegetable residues of all kinds) the necessary sanitation and pathogen reduction is ensured by the AD process itself. Some process parameters, such as temperature, retention time inside the digester, pH etc., have direct or indirect influence on the sanitation efficiency of the AD process.

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[3] (EC)No1774/2002 "laying down health rules concerning animal by-products not intended for human consumption" is available for download in full text from www.big-east.eu

Temperature

The process temperature has a sanitation effect on the supplied substrates. In case of pre-treatment of feedstock, the efficiency of pathogen reduction increases with the increasing temperatures.

Retention time

In the case of biogas plants treating animal manure and slurries, vegetable biomass from farming activities as well as other non-problematic feedstock types, sanitation is a result of combined temperatures and MGRT.

The influence of temperature and MGRT on destruction of pathogens is highlighted in Table 9.4, showing decimation times for some common pathogen types from animal slurries. In case of e.g. *Salmonella typhi murium*, the destruction of 90% of the population occurs in 0,7 hours in a digester running at 53°C (thermophilic digestion), in 2,4 days in a digester operating at 35°C (mesophilic digestion), but the same reduction of Salmonella can take 2 to 6 weeks at ambient temperature, in untreated slurry.

pH-value

The reduction of micro-organisms (bacteria) can occur in acid or alkaline environment. For this reason, pre-hydrolysis of certain biomass types causes a significant drop in pH-value and reduces micro-organisms up to 90% (caused by a toxic effect of organic acids).

Table 9.4 The *decimation time (T-90) of some pathogenic bacteria - comparison between animal slurry treated by AD and the untreated slurry (BENDIXEN 1999)**

Bacteria	Slurry treated by AD		Untreated slurry	
	53°C (thermophilic temperature) hours	35°C (mesophilic temperature) days	18-21°C weeks	6-15°C weeks
Salmonella typhi murium	0,7	2,4	2,0	5,9
Salmonella dublin	0,6	2,1	-	-
Escherichia coli	0,4	1,8	2,0	8,8
Staphilococcus aureus	0,5	0,9	0,9	7,1
Mycobacterium paratuberculosis	0,7	6,0	-	-
Coliform bacteria	-	3,1	2,1	9,3
Group of D-Streptococi	-	7,1	5,7	21,4
Streptococcus faecalis	1,0	2,0	-	-

* Decimation time T-90 is the time of survival of the observed micro-organisms. *The decimation time T-90, is defined as the time taken for viable counts of a population to decrease by one logarithmic unit (log_{10}), which is equivalent to a 90% reduction (SCHLUNDT, 1984).*

Origin of liquid manure

The lifetime of pathogens depends on the origin of liquid manure. *Salmonellae* for instance survive longest in cattle slurry, but pig slurry, on the other hand, contains more infectious organisms due to higher livestock density and presence of pathogens in the feed.

Positive/negative effects

Protective agglomeration of micro-organisms (bacteria) can prolong the inactivation process of pathogens.

Dry matter content

Some salmonella traits survive longest at a DM-content of more than 7%.

Ammonia content

Inactivation of pathogens is more effective in substrates with high ammonia content. As ammonia concentration in digestate is higher than in raw slurry, so is the efficiency of pathogen inactivation.

Digester system

In fully mixed digesters, the fresh feedstock can always contaminate the already sanitised substrate. Even in a plug flow reactor, where the particles move evenly through the reactor, short cuts cannot be prevented. Therefore, a minimum retention time in mixed reactors cannot be fully guaranteed. This can only be ensured in a batch (discontinuous) system, where the digester is firstly filled up and then completely emptied after digesting (e.g. batch method of dry AD system).

9.4.3 Indicator organisms

It is impossible to analyse digestate for all the pathogenic species that may be present, so there is a requirement to identify indicator organisms that may be reliably used to evaluate the efficiency of pathogen reduction in digestate. The use of indicator organisms to evaluate potential pathogen kill relies on activation, growth and infectivity of the test organisms.

One of the most used methods is the log10 of FS (*Faecale Streptococci),* which is based on the measurement of the *Faecale Streptococci* in digestate. Several veterinary research programmes in Denmark investigated the survival of bacteria, viruses and parasite eggs in animal manures under varying storage and anaerobic treatment conditions. The indicator organism *Faecal streptococci (enterococci)* (FS) was chosen because this kind of streptococcus survives the thermal treatment long after other pathogenic bacteria, viruses and parasite eggs are killed or lose their viability.

In Germany, the supplying of sewage sludge and biowaste, as feedstock for anaerobic co-digestion plants was investigated from a hygiene/ sanitation viewpoint. The requirements already put in place, concerning hygienic aspects of aerobic compost production, were used as guidelines, and many of the potential indicator organisms used in public health microbiology were rejected because of their existing prevalence in soil and water environments. With respect to co-digestion of biowaste, it was concluded that the absence of *Salmonella* provided the best index of effective sanitation in co-digestion AD plants. *Salmonella sp*. were shown to be present in >90% of biowaste bins sampled. Unlike the log10 of FS method, used in Denmark, the *Salmonella* test procedure requires pre-enrichment and enrichment cultivation stages in buffered peptone water and selective media, prior to positive identification.

The necessity to ensure phyto-hygiene was also investigated in Germany. Unlike the bacterial system, there are no recognised indicator organisms for potential plant pathogen presence. The only indicator which is widely distributed in household biowastes is tomato seeds. Consequently, the term "phytohygienic safety" has been defined, in Germany, as the absence, in treated wastes and wastewaters, of more than two tomato seeds, capable of germination, and/ or reproducible parts of plants per litre of treated waste.

Similar studies highlighted the effect of temperature on inactivation of viruses. For the majority of the viruses tested, heat was found to be the single, most important virucidal. In the case of parvovirus, other factors than heat substantially contributed to overall loss of viability. This is in line with the findings of other researchers, showing that factors such as high pH, ammonia, detergents and microbial metabolites may contribute to viral inactivation.

9.4.4 Requirements for sanitation

A number of European countries have national regulations requiring hygiene and sanitation standards in biogas plants digesting animal manure from several farms or co-digesting animal manure and organic wastes.

One of the most important European regulations affecting the biogas sector is the so-called *Animal By-Product Regulation EC 1774/2002*, concerning treatment and recycling of by-products of animal origin. The regulation identifies three main categories of animal by-products and specifies the treatment and sanitation requirements, the necessary equipment etc. According to EC 1774, there are types of animal by-products (*Category 1)* which is not permitted to be treated in biogas plants (Table 9.5).

Table 9.5 Animal by-products not intended for human consumption: categories and rules for their utilisation, according to EC1774/2002

Category and description	Rules for utilisation
1. Animals suspected to be infected with TSE, specific risk material - Animals, other than farm and wild animals, spec. pets, zoo and circus animals. - Catering waste from means of transport operating internationally	Always destruction – incineration
2. Manure from all species and digestive tract content from mammalians - All animal materials collected when treating wastewater from slaughter-houses or from category 2 processing plants, except from cat.1 slaughter-house wastewater treatment plants. - Products of animal origin, containing residues of veterinary drugs. Dead animals, others than ruminants.	For AD must be pressure sterilised, for 20 minutes at 133^{0}C and 3 bar. NB: Manure and digestive tract content can be used for AD without pre-treatment.
3. All parts of slaughtered animals, declared fit for human consumption, or not affected by any signs of diseases - Hides, skins,	For AD must be sanitised in separate tanks for 1hour at 70 ^{0}C.

With the exception of liquid manure, stomach and intestines content (separated from stomach and intestines), milk and colostrums (allowed without pre-treatment, provided no hazard of spreading serious disease exists) all animal by-products of *Category 2* must be steam pressure sterilised at ≥ 133°C, ≥ 3 bar, before processing in a biogas plant, and the thermal treatment must be carried out for at least 20 minutes after reaching the core temperature of 133^{o}C, in a plant authorised for that reason. The particle size of treated substrate must be < 50 mm.

For kitchen and food wastes and former foodstuff which have not been in contact with untreated, raw animal by-products, the national requirements apply. For treatment of other animal by-products of *Category 3* the following applies: Thermal pasteurisation must be carried out at 70°C for 60 minutes. The treated substrate must have a particle size < 12 mm.

In addition to compulsory thermal treatment, the Animal By-Product Regulation defines many other compulsory process conditions for the operation of biogas plants and the hygienic requirements for the end product.
In the case of kitchen and food waste of *Category 3*, the responsible national authorities can authorise exceptions to the above-mentioned approval and processing requirements, with the condition that equivalent sanitation is applied (Table 9.6). The main provision for the

authorisation of alternative processing methods is the proof of an equivalent destruction of all pathogenic germs for pasteurisation.

Table 9.6 Example from Denmark, of controlled sanitation, equivalent to 70°C for 1 hour (BENDIXEN 1995)

Temperature	Retention time (MGRT) in a thermophilic digestion tank [a]	Retention time(MGRT) by treatment in a separate sanitation tank [b]	
		before or after digestion in a thermophilic reactor tank [c]	before or after digestion in a mesophilic reactor tank [d]
52,0°C	10 hours		
53,5°C	8 hours		
55,0°C	6 hours	5,5 hours	7,5 hours
60,0°C		2,5 hours	3,5 hours

The treatment should be carried out in a digestion tank, at thermophilic temperature, or in a sanitation tank combined with digestion in a thermophilic or a mesophilic tank. The specific temperature/ MGRT combinations should be respected.

a) Thermophilic digestion is in this case at 52°C. The hydraulic retention time (HRT) in the digester must be at least 7 days
b) Digestion may take place either before or after pasteurisation
c) See point a)
d) The mesophilic digestion temperature must be from 20 °C to 52 °C. The hydraulic retention time must be at least 14 days.

Sanitation requirements are different according to the type of biogas plant (thermopilic or mesophilic process). Furthermore, for the collective treatment of materials of different categories the most stringent regulation applicable is deployed.

For kitchen, food waste and former foodstuffs, which have not been in contact with untreated, raw animal by-products, the following parameters for AD as a thermophilic process must be ensured: temperature ≥ 55°C, hydraulic retention time 20 days with a guaranteed minimum dwell time of 24 hours, particle size ≤ 12 mm.

In mesophilic biogas plants (temperature range around 37°C) thermal sanitation only takes place to a limited extent. Here, sanitation is to be achieved through heat-treating all materials containing domestic kitchen wastes, or by relevant proof of a sufficient reduction of pathogenic agents.

To avoid risks of infections, the regulation requires a strict separation of animal husbandry and biogas plant locations. Transport, intermediate storage, necessary pre-treatment (mincing, particle size reduction) as well as processing in the biogas plant are strictly regulated.

The same applies to the necessary cleaning sectors, cleaning appliances, disinfection areas, pest control, record and documentation obligations, hygienic controls and proper maintenance of all installations and calibration of all measuring instruments. Furthermore, all biogas plants must have an officially authorised laboratory at their disposal or make use of the services of an external authorised laboratory for analysing samples and running tests of pathogen reduction efficiency.

The area of the biogas plant must be separated into clean and contaminated. The two areas must be kept strictly separated. Cleaning facilities for transport vehicles, vacuum tankers and for the staff of the plant must be established as well. Figure 9.1 shows an example of standard procedure for the cleaning of biomass transport vehicles at Ribe Biogas Plant in Denmark.

In order to avoid empty drive, the vacuum tanker transports fresh slurry from the farmers to the biogas plant and digested slurry from the biogas plant to the farmers. To avoid contamination between fresh and digested slurry, the tanker must be cleaned after every transport, according to the above described procedure. Contamination between farms is avoided by servicing one farm at the time and avoiding drives between farms.

Standard procedure of cleaning the slurry transport vehicles:

- When the biomass content is completely drained off the vacuum tank, all the inner surfaces of the tank are flushed out with tap water, until the washes are totally clear.
- When the tank is empty and rinsed of, all the inner surfaces are spooled with 0,2% NaOH dissolution, at least 200 litters for a larger tank and at least 150 litters for a small one.
- After 2 minutes respite, the tank is ready to be refilled with digested biomass.
- While disinfection is taking place, all the exterior parts of the tank and the vehicle are rinsed and disinfected, in particular the wheels.

Figure 9.1 Example of standard cleaning procedure from Ribe biogas plant in Denmark

10 Economy of biogas plants

10.1 Financing the biogas project

Biogas projects demand high investments. Financing is therefore one of the key elements in order to ensure project viability. The financing scheme of a biogas plant project differs from country to country, but in general, low interest long–term loans are used. Ordinary mortgage loans are not frequently used. The index-regulated annuity loans are low-interest loans, which secure the investor against inflation through a re-evaluation of the unpaid debts according to the inflation rate. The pay-back period is more than 20 years. This type of loan proved to be the most suitable for financing the construction of the biogas plants, meeting the demands for long maturity, low interest and low initial instalments. The disadvantages of such loans are that they are raised by ordinary sales of bonds, at the stock exchange market price, implying a depreciation risk that may induce some uncertainty in the planning phase.

In countries like Denmark, biogas projects are e.g. financed by means of index-regulated annuity loans, guaranteed by the municipalities. Most of the past biogas projects received also supplementary government subsidies, representing up to 30% of the investment costs of the project.

10.2 Economic forecast of a biogas plant project

A single farmer, a consortium of farmers or a municipality are usually the entrepreneurs likely to implement successful biogas projects. The success of the project depends on some factors that can be controlled and influenced by strategic decisions concerning investment and operational costs. Choosing the best technology in respect of level of investment and operational costs is very difficult. If tendering a biogas plant, it is important receive offer on operational cost like:

- Operational cost of CHP incl. all services and spare parts (amount/kWh)
- Maintenance costs of biogas plant in total. (% of investment/year)
- Own electrical energy demand, including demand of CHP (kWh/year)
- Average working hours/day of staff (maintenance and feeding the system)

The success of the project is also influenced by some factors that cannot be controlled such as:

- Interest terms
- Grid access and feed in tariffs
- World market prices for feedstock (e.g. energy crops)
- Competition for feedstock from other sectors

Industrial waste collectors face problems securing long term availability of the feedstock. This could be a problem because the waste recycling market is highly competitive and contracts with waste producers are rarely for periods longer than five years.

Quite often, before a bank offers to finance the biogas plant project, the economical long term success of the project must be proven by a study/ calculation of profitability. The calculation is normally done within the preliminary planning by an experienced planning/ consulting company (see Chapter 8.1), but in many cases, especially in the case of single farm based biogas projects, this work can be done by the project developer, with two consequently advantages: the project developers/ partners are forced to have a very close view to the different aspects of the project and, in case of cancelling the project, no external costs have occurred.

In case of a biogas plant treating municipal waste, it is recommended to mandate an experienced consulting company. Waste treatment plants are much more complex regarding handling of feedstock, biological stability of the system and the whole plant design, compared to a farm based plant.

For case specific calculation of the economic forecast, a calculation model was elaborated (attached as CD), allowing the preliminary estimation of costs, plant size, dimensioning, technical outline etc. The calculation model as well as the guidelines for its utilisation are also available for free download at http://www.big-east.eu)

10.2.1 Conclusions of economic forecast of the biogas plant project

Having done the pre-calculations using the Big<East calculation tool as recommended in Chapter 10.2, the result is a model of the economy of the project.

As stated before, the operational costs and the investment costs can be influenced by strategic decisions. For example by choosing the best adapted technology. So, if labour is cheap in your country, than it might be cheaper engaging more people than spending money for automation of a plant.

The revenue side of a project is difficult to influence. The feed in tariffs are set by the government. In case of waste treatment plants, the tipping fees are market prices. There are other possibilities of improve the revenue side:

- Using/selling the produced heat
- Selling digestate as a fertilizer

If the project obtains an internal rate of return (IRR) lower than 9%, you should reconsider all the project premises, and improve some of them. If the IRR rate is higher than 9%, the premises are good and it is worth continuing the project and moving to the next planning phase. It is important to compare the assumptions with the material reality. This helps to get a realistic idea of the biogas plant itself, the needed space, the true mass current and the real building costs.

The calculation model is useful for providing the rough information which is necessary to kick start the actual planning phase. For the next steps of project, finding an independent and reliable planning partner is mandatory (see the project steps described in chapter 8.1.)

Best of luck!

Annexes

Annex 1. Glossary, conversion units and abbreviations

Glossary

Acid:	Traditionally considered any chemical compound that, when dissolved in water, gives a solution with a pH less than 7,0.
Ammonia:	A gaseous compound of hydrogen and nitrogen, NH_3, with a pungent smell and taste.
Anaerobic bacteria:	Micro-organisms that live and reproduce in an environment containing no "free" or dissolved oxygen. Used for anaerobic digestion.
Anaerobic digestion (Syn. Digestion, fermentation):	A microbiological process of decomposition of organic matter, in the complete absence of oxygen, carried out by the concerted action of a wide range of micro-organisms. Anaerobic digestion (AD) has two main end products: *biogas* (a gas consisting of a mixture of methane, carbon dioxide and other gases and trace elements) and *digestate* (the digested substrate). The AD process is common to many natural environments and it is applied today to produce biogas in airproof reactor tanks, commonly named digesters.
Barrel of oil equivalent (boe):	The amount of energy contained in a barrel of crude oil, i.e. approx. 6,1 GJ, equivalent to 1 700 kWh. A "petroleum barrel" is a liquid measure equal to 42 U.S. gallons (35 Imperial gallons or 159 litters); about 7,2 barrels are equivalent to one tonne of oil (metric).
Base:	Traditionally considered any chemical compound that, when dissolved in water, gives a solution with a pH greater than 7,0.
Batch feed:	A process by which the reactor is filled with feedstock in discrete amounts, rather than continuously.
Biochemical conversion:	The use of biochemical processes to produce fuels and chemicals from organic sources.
Bioenergy (Syn. Biomass energy):	Useful, renewable energy produced from organic matter. The conversion into energy of the carbohydrates in organic matter. Organic matter may either be used directly as a fuel or processed into liquids and gases.
Biogas:	A combustible gas derived from decomposing biological waste under anaerobic conditions. Biogas normally consists of 50-60% methane.

Biological Oxygen Demand (BOD):	Chemical procedure for determining how fast biological organisms use up oxygen in a body of water.
Biomass feedstock:	Organic matter available on a renewable basis. Biomass includes forest and mill residues, agricultural crops and wastes, wood and wood wastes, animal wastes, livestock operation residues, aquatic plants, fast-growing trees and plants, and municipal and industrial wastes.
Bioreactor (Syn. Digester):	Device for optimising the anaerobic digestion of biomass and/ or animal manure, and possibly to recover biogas for energy production.
Capacity:	The maximum power that a machine or system can produce or carry safely (The maximum instantaneous output of a resource under specific conditions). The capacity of generating equipment is generally expressed in kilowatts or megawatts.
Chips:	Woody material cut into short, thin wafers. Chips are used as a raw material for pulping and fibreboard or as biomass fuel.
Centralised Anaerobic digestion (CAD):	Supplying slurry from several animal farms to a centrally located biogas plant, to be co-digested with other suitable feedstock.
Certificates RECs):	A tradable commodity proving that certain electricity is generated using renewable energy sources. Typically one certificate represents generation of 1 Megawatt hour (MWh) of electricity.
Co-generation**:**	see combined heat and power generation (CHP)
Combined heat and power generation (CHP) (Syn. Co-generation):	The sequential production of electricity and useful thermal energy from a common fuel source. Reject heat from industrial processes can be used to power an electric generator (bottoming cycle). Conversely, surplus heat from an electric generating plant can be used for industrial processes, or space and water heating purposes (topping cycle).
CO_2 –equivalents:	CO_2 equivalent is a unit used to standardise measurements of. For example, tonne for tonne, methane is a greenhouse gas that is 21 times more powerful than carbon dioxide in causing the global greenhouse effect. Therefore one tonne of methane represents 21 tonnes of CO_2 equivalent.
Dedicated Energy Crops: (DEC)	Crops grown specifically for their fuel value. These include food crops such as corn and sugarcane, and non-food crops such as poplar trees and switchgrass. Currently, two energy crops are under development: short-rotation woody crops, which are fast-growing hardwood trees harvested in 5 to 8 years, and herbaceous energy crops, such as perennial grasses, which are harvested annually after taking 2 to 3 years to reach full productivity.
Digestate: (Syn. AD residues, digested biomass,	The treated/ digested effluent from the AD process.

digested slurry)	
Digestion:	see Anaerobic Digestion
Effluent:	The liquid or gas discharged from a process or chemical reactor, usually containing digestate from that process.
Emissions:	Fumes or gases that come out of smokestacks and tailpipes, seep from inside factories or enter the atmosphere directly from oil well flares, garbage dumps, rotting vegetation and decaying trees and other sources. They include carbon dioxide, methane and nitrous oxide, which cause most of the global greenhouse effect.
Energy balance:	Quantify the energy used and produced by the process.
Feedstock:	Any material which is converted to another form or product.
Fermentation:	see Anaerobic digestion
Fly ash:	Small ash particles carried in suspension in combustion products.
Fossil fuel:	Solid, liquid, or gaseous fuels formed in the ground after millions of years by chemical and physical changes in plant and animal residues under high temperature and pressure. Crude oil, natural gas, and coal are fossil fuels.
Fuel cell:	A device that converts the energy of a fuel directly to electricity and heat, without combustion.
Gas turbine (syn. Combustion turbine):	A turbine that converts the energy of hot compressed gases (produced by burning fuel in compressed air) into mechanical power. The used fuel is normally natural gas or fuel oil.
Gasification:	The process in which a solid fuel is converted into a gas; also known as pyrolitic distillation or pyrolysis.
Gigawatt (GW):	A measure of electric capacity equal to 1 billion watts or 1 million kilowatts.
Global warming:	A gradual warming of the Earth's atmosphere reportedly caused by the burning of fossil fuels and industrial pollutants.
Green certificates (Syn. Renewable energy	
Generator:	A device for converting mechanical energy to electrical energy.
Greenhouse effect:	The effect of certain gases in the Earth's atmosphere in trapping heat from the sun.
Greenhouse gas (GHG):	Gases that trap the heat of the sun in the Earth's atmosphere, producing the greenhouse effect. The two major greenhouse gases are water vapor and carbon dioxide. Other greenhouse gases include methane, ozone, chlorofluorocarbons, and nitrous oxide.

Grid:	The electric utility companies' transmission and distribution system that links power plants to customers through high power transmission line service (110 kilovolt [kV] to 765 kV); high voltage primary service for industrial applications and street rail and bus systems (23 kV-138 kV); medium voltage primary service for commercial and industrial applications (4 kV to 35 kV); and secondary service for commercial and residential customers (120 V to 480 V). Grid can also refer to the layout of a gas distribution system of a city or town in which pipes are laid in both directions in the streets and connected at intersections.
Grid system:	An arrangement of power lines connecting power plants and consumers over a large area.
Heat exchanger:	Device built for efficient heat transfer from one fluid to another, whether the fluids are separated by a solid wall so that they never mix, or the fluids are directly contacted.
Heat transfer efficiency:	Useful heat output released/ actual heat produced in the firebox.
Heating value:	The maximum amount of energy that is available from burning a substance.
Installed capacity:	The total capacity of electrical generation devices in a power station or system.
Joule (J):	Metric unit of energy, equivalent to the work done by a force of one Newton applied over a distance of one meter. 1 joule (J) = 0,239 calories; 1 calorie (cal) = 4,187 J.
Kilovolt (kV):	1 000 volts. The amount of electric force carried through a high-voltage transmission line is measured in kilovolts.
Kilowatt (kW):	A measure of electrical power equal to 1 000 watts. 1 kW = 3,413 Btu/hr = 1,341 horsepower.
Kilowatt-hour (kWh):	The most commonly-used unit of measure telling the amount of electricity consumed over time. It means one kilowatt of electricity supplied for one hour.
Mesophilic digestion:	Takes place optimally around 37°-41°C or at ambient temperatures between 20°-45°C where mesophiles are the primary micro-organism present.
Methane (CH_4):	A flammable, explosive, colourless, odourless, tasteless gas that is slightly soluble in water and soluble in alcohol and ether; boils at –161,6ºC and freezes at –182,5ºC. It is formed in marshes and swamps from decaying organic matter, and is a major explosion hazard underground. Methane is a major constituent (up to 97%) of natural gas, and is used as a source of petrochemicals and as a fuel.
Micro-turbine:	Small combustion turbine with an output of 25 to 500 kW. Micro-turbines are composed of a compressor, combustor, turbine, alternator, recuperator and generator. Relative to other technologies for small-scale power generation, micro-turbines offer a number of advantages, including: a small number of moving parts, compact size, light weight,

	greater efficiency, lower emissions, lower electricity costs, potential for low cost mass production, and opportunities to utilise waste fuels.
Mini-grid:	An integrated local generation, transmission and distribution system serving numerous customers.
Municipal solid waste (MSW):	All types of solid waste generated by a community (households and commercial establishments), usually collected by local government bodies.
Oil equivalent:	The tonne of oil equivalent (toe) is a unit of energy: the amount of energy released by burning one tonne of crude oil, approx. 42 GJ.
Photosynthesis:	Process by which chlorophyll-containing cells in green plants concert incident light to chemical energy, capturing carbon dioxide in the form of carbohydrates.
Pilot scale:	The size of a system between the small laboratory model size (bench scale) and a full-size system.
Power:	The amount of work done or energy transferred per unit of time.
Process heat:	Heat used in an industrial process
pH:	An expression of the intensity of the alkaline or acidic strength of water. Values range from 0-14, where 0 is the most acidic, 14 is the most alkaline and 7 is neutral.
Plant:	A facility containing prime movers, electric generators, and other equipment for producing electric energy.
Renewable resources:	Naturally replenishable, but flow-limited energy resources. They are virtually inexhaustible in duration, but limited in the amount of energy that is available per unit of time. Some (such as geothermal and biomass) may be stock-limited in that stocks are depleted by use, but on a time scale of decades, or perhaps centuries, they can probably be replenished. Renewable energy resources include: biomass, hydro, geothermal, solar and wind. In the future they could also include the use of ocean thermal, wave, and tidal action technologies. Utility renewable resource applications include bulk electricity generation, on-site electricity generation, distributed electricity generation, non-grid-connected generation, and demand-reduction (energy efficiency) technologies.
Renewable energy:	see Bioenergy
Sludge:	Biosolids separated from liquids during processing. Sludge may contain up to 97% water by volume.
Substrate:	see Biomass feedstock
Sustainable:	An ecosystem condition in which biodiversity, renewability and resource productivity are maintained over time.
Total solids	

(Syn. Dry solid):	The residue remaining when water is evaporated away from the residue and dried under heat.
Thermophilic digestion:	Anaerobic digestion which takes place optimally around 50°C-52°C but also at elevated temperatures up to 70°C, where thermophiles are the primary micro-organisms (bacteria) present.
Turbine:	A machine for converting the heat energy in steam or high temperature gas into mechanical energy. In a turbine, a high velocity flow of steam or gas passes through successive rows of radial blades fastened to a central shaft.
Volatile solids (VS):	Those solids in water or other liquids that are lost on ignition of the dry solids at 550°C.
Volatile fatty acids (VFA):	These are acids that are produced by microbes in the silage from sugars and other carbohydrate sources. By definition they are volatile, which means that they will volatilise in air, depending on temperature. These are the first degradation product of anaerobic digestion prior to methane creation.
Volts:	A unit of electrical pressure. It measures the force or push of electricity. Volts represent pressure, correspondent to the pressure of water in a pipe. A volt is the unit of electromotive force or electric pressure analogous to water pressure in pounds per square inch. It is the electromotive force which, if steadily applied to a circuit having a resistance of one ohm, will produce a current one ampere.
Watt (W):	A standard unit of measure (SI System) for the rate at which energy is consumed by equipment or the rate at which energy moves from one location to another. It is also the standard unit of measure for electrical power. The term 'kW' stands for "kilowatt" or 1 000 watts. The term 'MW' stands for "Megawatt" or 1 000 000 watts.

Conversion units

Kilowatt (kW) = 1 000 Watts
Megawatt (MW) = 1 000 kW
Gigawatt (GW) = 1 million kW
Terawatt (TW) = 1 thousand million kW
1 Joule (J) = 1 Watt second = 278 x 10^-6 Wh
1Wh = 3 600 J
1 cal = 4,18 J
1 British Thermal Unit (BTU) = 1 055 J
1 cubic meter (m^3) = 1 000 liter (L)
1 bar = 100 000 pascal (Pa)
1 millibar = 100 Pa
1 psi = 6894,76 Pa
1 torr = 133,32 Pa
1 millimeter mercury (0°C) = 133,32 Pa
1 hectopascal (hPa) = 100 Pa

Abbreviations

AD – Anaerobic digestion
BOD – Biological oxygen demand
CHP – Combined heat and power
C:N ratio – Carbon to nitrogen ratio
COD – Chemical oxygen demand
DEC – Dedicated energy crops
DM – Dry matter
FF – Fresh feedstock
GHG – Greenhouse gases
HRT – Hydraulic retention time
kWh – Kilowatt hour
kWh_{el} – Electrical kilowatt hour
MGRT – Minimum guaranteed retention time
N-P – Nitrogen to phosphorus
NPK –Nitrogen, phosphorus and potassium
oDM – Organic fraction of dry matter
ppm – Parts per million (1ppm = 0,0001%)
RD&D – Research development and demonstration
TLV – Threshold limit value
TS – Total solids
VFA – Volatile fatty acids
VS – Volatile solids

Annex 2. Literature

Agapitidis I. and Zafiris C. (2006). 'Energy Exploitation of Biogas: European and National perspectives'. 2nd International Conference of the Hellenic Solid Waste Management Association.

Al Seadi, T. (2001). Good practice in quality management of AD residues from biogas production. Report made for the International Energy Agency, Task 24- Energy from Biological Conversion of Organic Waste. Published by IEA Bioenergy and AEA Technology Environment, Oxfordshire, United Kingdom.

Al Seadi, T.; Holm Nielsen J. (2004). Utilisation of waste from food and agriculture: Solid waste: Assesment, Monitoring and Remediation; Waste management series 4; ELSEVIER; ISBN 0080443214, 735-754.

Al Seadi, T.; Moeller H., B. (2003). Separation of slurry - A potential option for the animal production sector. Proceedings report of European Biogas Workshop "The Future of Biogas in Europe III", October 2-4, Esbjerg, Denmark.

Amon, T. et al. (2006). Optimierung der Methanerzeugung aus Energiepflanzen mit dem Methanenergiewertsystem Published by Bundesministerium für Verkehr, Innovation und Technologie, Wien, Austria.

Amon, T.; Kryvoruchko, V.; Amon, B.; Moitzi, G.; Buga, S.; Lyson, D. F.; Hackl, E.; Jeremic, D.; Zollitsch, W.; Pötsch, E. (2003). Optimierung der Biogaserzeugung aus den Energiepflanzen Mais und Kleegras.Published by Bundesministeriums für Land- und Forstwirtschaft, Umwelt- und Wasserwirtschaft, Wien, Austria.

Amon, T.; Kryvoruchko, V.; Amon, B.; Schreiner, M.(2004). Untersuchungen zur Wirkung von Rohglycerin aus der Biodieselerzeugung als leistungssteigerndes Zusatzmittel zur Biogaserzeugung aus Silomais, Körnermais, Rapspresskuchen und Schweinegülle. Published by Südsteirische Energie- und Eiweißerzeugung Reg.Gen.m.b.H., Mureck, Austria.

Amon, T.; Machmüller, A.; Kryvoruchko, V.; Milovanovic, D.; Hrbek, R.; Eder, M. W.; Stürmer, B.(2007). Optimierung der Methanausbeute aus Zuckerrüben, Silomais, Körnermais, Sonnenblumen, Ackerfutter, Getreide, Wirtschaftsdünger und Rohglyzerin unter den Standortbedingungen der Steiermark. Published by Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft in collaboration with Amt der Steiermärkischen Landesregierung, Wien, Graz, Austria.

Angelidaki, I. et al. (2004). Environmental Biotechnology. AD – Biogas Production. Environment & Resources DTU, Technical University of Denmark.

ASPO-Association for the study of the peak oil (2008). http://www.peakoil.net/

Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz (STMUGV) (2004). Biogashandbuch Bayern. - www.ustmugv.bayern.de

Bendixen, H.J. et al. (1995). Smitstofreduktion i biomasse. Landbrug og

Fiskeriministeriet. Veterinærdirektoratet.

Birkmose, T. (2002). Centralised Biogas Plants. Landscentret, Planteavl. ISBN 87 7470 829 5.

Boukis I., K. Sioulas, A. Chatziathanassiou, A. Kakaniaris and D. Mavrogiorgos (2002). Development of networking and synergies for Anaerobic Digestion energy schemes based on agro-industrial wastes in Southern Europe. The citrus-processing industries case study. "Energy Efficiency and Agricultural Engineering" Proceedings of the Union of Scientists, Rousse-Bulgaria 2002, Volume I, 255-263. In English.

Bundesministerium für Wirtschaft und Arbeit (2007). Technische Grundlage für die Beurteilung von Biogasanlagen. Published by Bundesministerium für Wirtschaft und Arbeit, Wien, Austria.

Chatziathanassiou A., K. Sioulas, D. Mavrogiorgos, A. Veneti and I. Boukis (2002). Stakeholders' perceptions for Anaerobic Digestion Energy Schemes in Greece. 12th European Conference and Technology Exhibition on biomass for Energy, Industry and Climate Protection, 17-21 June 2002, Amsterdam, The Netherlands. In English.

Environmental Protection Agency ;An Gníomhaireacht um Chaomhnú Comhshaoil. (2002).P.O. Box 3000, Johnstown Castle Estate, County Wexford, Ireland. ISBN: 1-84095-083-8

European Parliament (2002). Regulation (EC) no 1774/2002 of the European Parliament and of the Council of 3 October 2002 laying down health rules concerning animal by-products not intended for human consumption.

FNR (2006). Handreichung Biogasgewinnung und – Nutzung. – 3. überarbeitete Auflage; Fachagentur Nachwachsende Rohstoffe edt.; Germany; ISBN 3-00-014333-5

Hansen, M.N.; Birkmose, T.; Mortensen, B.; Skaaning, K. (2004). Miljøeffekter af bioforgasning og separering af gylle. Grøn Viden, Markbrug nr. 296.

Hjort-Gregersen, K. (1998). Danish Farm Scale Biogas Concepts- at the point of commercial break trough. Danish Institute of Agricultural and Fisheries Economics. Proceedings of the International Conference Würzburg, Germany: Biomass for Energy and Industry, 8-11 June 1998, p 641-643.

Hornbachner, D.; Hutter, G.; Moor, D. (2005). Biogas-Netzeinspeisung – Rechtliche, wirtschaftliche und technische Voraussetzungen in Österreich. Published by Bundesministerium für Verkehr, Innovation und Technologie, Wien, Austria.

Ivan Simeonov, Dencho Denchev and Bayko Baykov (2006). "Development of new technologies for production of heat and electric power from organic wastes for increasing the economic efficiency of the final products", Advances in Bulgarian Science, № 1, 15-24,

Jäkel K. (2002). Landwirtschaftliche Biogaserzeugung und – verwertung – Managementunterlage; Sächsische Landesanstalt für Landwirtschaft, Germany

Jönsson, O. et al. (2001). Adding gas from biomass to the gas grid. Swedish Gas Center Report SGC 118.ISSN 1102-7371.

Kirchmeyr, F.; Kraus, J. (2005). Mit Biogas in das Erdgasnetz – Erste ö. Biogasaufbereitungs- und Einspeisungsanlage in Pucking. Published by ARGE Kompost & Biogas Österreich in collaboration with erdgas OÖ, Linz, Austria.

Krachler, M. M.; Dissemond, H.; Walla, C. (2003). BIOGAS - eine ökologische, volks- und betriebswirtschaftliche Analyse. Published by NÖ Landesakademie Bereich Umwelt und Energie, St. Pölten, Austria.

LandesEnergieVerein Steiermark (2003). Bauherrnmappe Biogas, Published by LandesEnergieVerein Steiermark, Graz, Austria.

LfU (2007). Biogashandbuch Bayern - Materialband. - Bayerisches Landesamt für Umwelt, Augsburg, Germany. http://www.lfu.bayern.de/abfall/fachinformationen/biogashandbuch/index.htm

Metcalf and Eddy (1979). Wastewater Engineering: Collection, Treatment, Disposal, McGraw-Hill, New York.

Meynell, P.J. (1976).Methane, Planning a Digester. Prism Press, Dorset, England.

Moller, H. et al. (2004). Methane productivity of manure, straw and solid fractions of manure. Biomass & Bioenergy 26, pp 485-495.

Nordberg, Å. (1999). EU and National Legislation of Relevance to Anaerobic Digestion.

Padinger, R. et al. (2006). Biogas Pilotanlage - Teilprojekt 1 - Stoffstromanalyse im Rahmen großtechnischer Versuche sowie quantitative und qualitative Bewertung der Einsatzstoffe. Published by Joanneum Research - Institut für Energieforschung, Graz, Austria.

Persson,M.(2007). Biogas-a renewablefuel for the transport sector for the present and the future. SGC, www.sgc.se.

Petz, W. (2000). Auswirkungen von Biogasgülledüngung auf Bodenfauna und einige Bodeneigenschaften. Published by Amt der Oberösterreichischen Landesregierung Landesrat für Wasserwirtschaft Dr. Achatz, Hallwang, Austria.

Preißler, D. et al. (2007). Anaerobic digestitionof energy crops without manure addition. 35.Symposium “ActualTasks ofn AgriculturalEngineering”, Opatija, Croatia, S. 363-370.

Rutz D., Janssen R., Epp C., Helm P., Grmek M., Agrinz G., Prassl H., Sioulas K., Dzene I., Ivanov I., Dimitrova D., Georgiev K., Kulisic B., Finsterwalder T., Köttner M., Volk S., Kolev N., Garvanska S., Ofiteru A., Adamescu M., Bodescu F., Al Seadi T. (2008). The Biogas Market in Southern and Eastern Europe: Promoting Biogas by Non-technical Activities. - Proceedings of the 16th European Biomass Conference and Exhibition; Valencia, Spain; ISBN 978-88-89407-58-1

Sioulas, K., Mavrogiorgos, D. and Chatziathanassiou, A. (2003). An assessment of social and environmental impacts and benefits associated with the development of the AnDigNet project in the 2nd International Conference on Ecological Protection of the Planet Earth, 5-8 June 2003, Sofia, Bulgaria.

Sioulas, K., Boukis, I., et. al. (1999). “Establishment of a network of competent partners for the treatment and energy valorisation, by means of Anaerobic Digestion of the residues generated by the citrus-processing industries (AnDigNet)” IPS-1999-00042, Final Report.

Stoyanov, M., B. Baykov, A. Danev (1996). “Development of Technological regimes for Producing Biogas from Buffalo Dung”, Bulgarian Journal of Agricultural Sciences, 2, 121 – 123;

Thrän D., Seiffert M., Müller-Langer F., Plättner A., Vogel A. (2007). Möglichkeiten einer Europäischen Einspeisungsstrategie. – Institut für Energie und Umwelt, Leipzig, Germany

Wolfsgruber, S.; Löffler, G.; Gross, R. (2005). ENERGIE AUS BIOGAS - Leitfaden für landwirtschaftliche Biogasanlagen. Published by Umwelt.Service.Salzburg in collaboration with Land Salzburg, Salzburg, Austria.

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