DiBiCoo
Digital global
Biogas
Cooperation

CATEGORIZATION OF EUROPEAN BIOGAS TECHNOLOGIES

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EXECUTIVE SUMMARY OF D2.2

The following document provides an overview of existing European biogas technologies.

After the introductory section about Anaerobic Digestion (AD), the text follows the logic of the biogas production process, progressing from on-site feedstock storage options and pre-treatment requirements to the various digester technologies. Special, detailed chapters are included on issues of particular relevance for all biogas plants (including, for example, a chapter on measurement, control and regulation technologies).

The upgrading of biogas to biomethane quality is introduced, along with other biogas applications, such as its GHG mitigation potential and use in Combined Heat & Power (CHP) plants.

Due to the huge amount of existing information available on this topic, it may be the case that not everything is included or considered extensively here. This guide is intended as a solid starting point in learning about anaerobic digestion; it cannot replace specialised training courses or professional planning.

The detailed descriptions of certain technologies do not imply any preference for a particular technology, service provider or device. Similarly, pictures showing company names are included for visualisation purposes only and should not be seen as an endorsement of any specific company or technology.

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SUMMARY OF THE DIBICOO PROJECT

The **Digital Global Biogas Cooperation (DiBiCoo)** project is part of the EU's Horizon 2020 Societal Challenge 'Secure, clean and efficient energy', under the heading 'Market Uptake Support'.

The target emerging and developing importing countries are Argentina, Ethiopia, Ghana, South Africa and Indonesia. Additionally, the project involves partners from Germany, Austria, Belgium and Latvia. The project started in October 2019 with a 33-month timeline and a budget of 3 Million Euros. It is implemented by the consortium and coordinated by the German Society for International Cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, or GIZ).

The overall objective of the project is to prepare markets in developing and emerging countries for the import of sustainable biogas/biomethane technologies from Europe. DiBiCoo aims to benefit both importing and exporting countries by facilitating dialogue between European biogas industries and biogas stakeholders or developers from emerging and developing markets. The consortium is working to advance knowledge transfer and experience sharing, with the aim of improving local policies so as to allow increased market uptake by target countries. This is facilitated via a digital matchmaking platform and classical capacity development mechanisms for improved networking, information sharing, and technical/financial competencies. Furthermore, DiBiCoo will identify five demo cases up to the investment stages in the 5 importing countries. In this way, the project will help to mitigate GHG emissions and increase the share of renewable energy generation in the global energy mix. The project also contributes to the UN Sustainable Development Goals (SDG 7) for 'Affordable and clean energy', among others.

Further information can be found on the DiBiCoo website: www.dibicoo.org.

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LIST OF ABBREVIATIONS

AD	Anaerobic digestion
CH_4	Methane
CHP	Combined Heat & Power
CO_2	Carbon dioxide
CSTR	Continuously Stirred Reactor
d	day
EGSB	Expanded granular sludge bed digestion
EU	European Union
GHG	Green House Gas
H_2S	Hydrogen Sulphide
HRT	Hydraulic retention time [d]
LEL	Lower explosive level
MCR	Measurement, control and regulation technique
NH_3	Ammonia
O_2	Oxygen
OLR	Organic loading rate [kg_{VS} m^{-3} d^{-1}]
PPE	Personal Protective Equipment
ppm	Parts per million
SVLFG	Sozialversicherung für Landwirtschaft, Forsten und Gartenbau
UASB	Upflow anaerobic sludge blanket digestion
UEL	Upper explosive limit
VFA	Volatile fatty acids
VS	Volatile solids

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1 INTRODUCTION: ANAEROBIC DIGESTION (AD)

Anaerobic digestion (AD) is a biotechnological process, in which microorganisms break down organic matter, generating two very valuable products – namely, digestate and a renewable energy source called biogas. This is a well-known process in nature, taking place in wetlands, at the bottom of lakes, in slurry tanks and in the rumen of ruminants. If the same process takes place within ambient air, we call it composting. In contrast to composting, however, anaerobic digestion makes it possible not only to recycle the nutrients, but also to convert organic carbon into biogas. The AD process requires the following conditions:

- Temperature above 5 °C
- Absence of oxygen
- Darkness
- Existence of biodegradable biomass
- Existence of moisture and nutrients

The AD process can be divided into four stages. Biologically speaking they are consecutive stages but they usually take place simultaneously inside the digester. The are (in order):

- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

During **hydrolysis**, the first process step, hydrolytic bacteria break down complex organic matter (carbohydrates, fats and proteins) into simple organic compounds like monosaccharides, fatty acids and other amino acids. In order to achieve this, hydrolytic bacteria produce enzymes which cause the organic matter to decompose. The optimal pH value for hydrolytic bacteria lies between pH 5 and pH 6; similarly, the enzymes produced also function best where the pH level is below pH 7.

The first of two fermentation stages makes up the second part of the process, known as **Acidification**. During this stage, fermentative bacteria further break down the products of the first step into lower fatty acids such as propionic-, butyric- and valeric acid, as well as carbon dioxide and also small quantities of alcohols, H_2S and lactic acid. As for hydrolytic bacteria, the optimal pH value for acidogenic bacteria lies between pH 4 and pH 6.

Acetogenesis is the third stage of the process and the second fermentation to occur. During this step, acetogenic bacteria break down propionic and butyric acid to form acetic acid, hydrogen and carbon dioxide. If the hydrogen partial pressure becomes too high, it may hinder the activity of the acetogenic bacteria, potentially causing the amounts of propionic and butyric acid to rise and interfere with the process.

The last step, **Methanogenesis**, sees the production of biogas by methanogenetic archaea. Of all four steps, this is the most sensitive and the archaea involved have the longest doubling time.

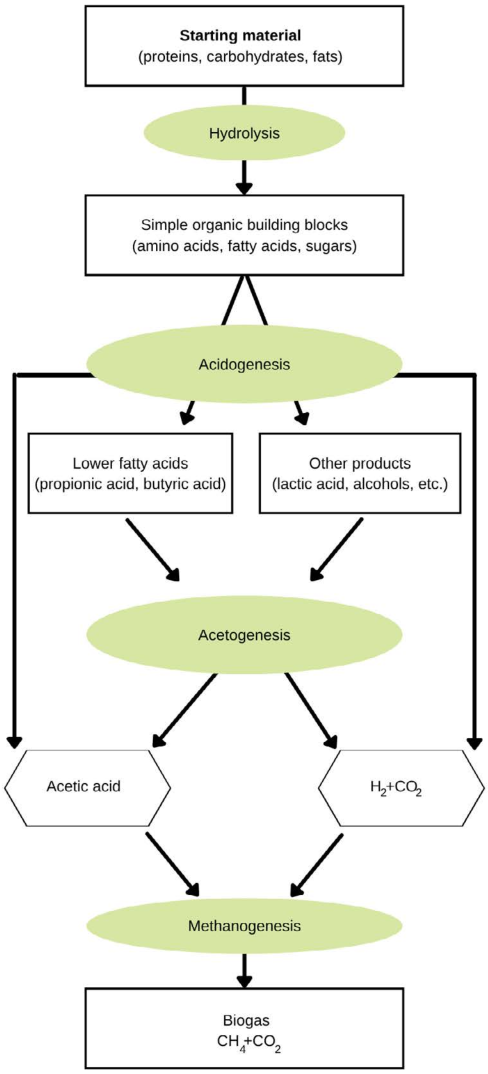


Figure 1: Scheme of the decomposing process of organic matter within AD; © FNR 2012.

Although these four steps and their respective bacteria are active simultaneously in the digester, they each behave differently and have different requirements for optimum performance. Table 1 gives a short overview of the various requirements of the different bacteria involved in anaerobic digestion.

Condition	Hydrolysis, Acidification	Acetogenesis, Methanogenesis
Favorite dry matter content	< 40 %	< 30 %
Ideal C:N proportion	10 – 45:1	20 – 30:1
Main nutrient demand C:N:P	80 – 125:5:1	80 – 125:5:1
Ideal pH value	5.2 – 6.3	6.8 – 7.5
Presence of Oxygen and light	No problem	strictly anaerobic inhibition already at oxygen content > 0.1 mg l^{-1}
Ideal temperature	20 – 35 °C	Mesophil: 38 °C Thermophil: 55 °C
Fluctuation of temperature	tolerant	Very sensitive, less than 1°C per day
Growth rates	fast	slow
Doubling time	< 48 h Aerobic: 20 min – 10 h Anaerobically: 1 – 48 h	> 9 h Acetogenic: 9 – 18 h Methanogenic: 48 – 72 h
Sensitive to inhibitors	low	High

Table 1: Different requirements of involved bacteria within anaerobic digestion process; © Gerardi 2003, Hecht 2008, Schulz, 2006.

Table 1 shows that it can, to some extent, represent a challenge for the anaerobic digestion process as a whole if the four steps take place simultaneously. Hydrolytic and acidification bacteria have a very fast doubling time, are not very sensitive to temperature changes and grow best at lower pH values. Methanogenic archaea are highly sensitive, do not like temperature changes of more than 1 °C per day, are very susceptible to light and oxygen and stop working at pH values below 6.5. The vulnerability of methanogenic archaea to lower pH levels, combined with the faster doubling time of the hydrolytic and acidification bacteria, is one of the most common reasons for the biogas process to stop. Additionally, the methanogenic archaea are more dependent on a number of micronutrients, including cobalt, nickel, molybdenum, selenium, copper and zinc. Copper and zinc are not usually in short supply if, for example, manure is used as the feedstock. The recommended amount of trace elements is shown in Table 2. Recommendations concerning the optimal levels of trace elements vary considerably, showing how difficult it is optimise a process based on living organisms. The same can be said about the optimum ratio of macro-elements. Ideally, the ratio of *C:N:P:S* should reach 600:15:15:3, but even the ratio of *C:N* varies from 10-30:10 (Paterson, 2012; Schulz 2006).

The following sections provide more details on a range of factors affecting the AD process.

Trace element	Range [mg l^{-1}]	Optimum [mg l^{-1}]
Co	0.003 – 10	0.12
Ni	0.005 – 15	0.015
Se	0.008 – 0.2	0.018
Mo	0.005 - 0.2	0.15
Mn	0.005 – 50	
Fe	0.1 - 10	

Table 2: Favorable concentrations of trace elements according to various sources; © Paterson, 2012.

1.1 INHIBITORS

Table 3 shows a number of inhibitors that can hinder the digestion process. As there are many factors that can affect process inhibition, the information given here should not be seen as definitive, nor as a comprehensive list of all possible inhibitors that may occur. They offer an overview of the problem, however, and demonstrate the sensitivity and importance of substrate receipt and prechecking. Products with a high protein content, for example, can cause N-inhibition because of their high nitrogen content. Raised amounts of Volatile Fatty Acids (VFA) can be an inhibiting factor, brought about when overfeeding of the reactor lowers the pH, or it can be a secondary effect of other inhibitors preventing the methanogenic archaea from consuming the VFA.

Inhibitor	Inhibitory Concentration	Comments
Oxygen	> 0.1 mg l^{-1}	Inhibition of obligate anaerobic methanogenic archaea
Hydrogen sulfide	> 50 mg l^{-1} H_2S	Inhibitory effect rises with falling pH value
Volatile fatty acids	2 000 mg l^{-1} acetic acid equivalent (pH = 7.0)	Inhibitory effect rises with falling pH value. High adaptability of bacteria
Ammonia	> 3 500 mg l^{-1} NH_4+ (pH = 7.0)	Inhibitory effect rises with rising pH value and rising temperature. High adaptability of bacteria
Heavy metals	Cu > 50 mg l^{-1} Zn > 150 mg l^{-1} Cr > 100 mg l^{-1}	Only dissolved metals have an inhibitory effect. Detoxification by sulphide precipitation
Disinfectants, antibiotics		Product-specific inhibitory effect

Table 3: Possible inhibitors in anaerobic digestion process; © Paterson, 2012.

	Active substance	Concentration [mg l-1] [ml l-1]	Impact on methane formation (100 % = nominal capacity) [%]
Antibiotics [mg l-1]	Bacitracin	100 10 3	68 68 80
	Flavomycin	50 10 3	104 101 100
	Lasalocid	100 10 3	25 102 105
	Monensin	5 2 0.5	35 35 38
	Spiramycin	50 10 2.5	44 46 46
	Tysolin	100 10 3	65 67 80
	Virginiamycin	50 10 3	46 73 81
synthetic chemo-therapeutics [mg l-1]	Arsanilic acid	100 10 3	54 88 90
	Furazolidon	200 50 3	41 93 97
	Sulfamethazin	100 20 3	101 99 102
	Olaquindox	100 10 1	4 32 35
disinfecting agents [ml l-1]	Chloroform	0.3 0.03	11 10
	Aldehyde, alcohols	0.16 0.016	14 83
	phenols	0.1 0.01	94 92
	Aldehyde quaternary ammonium compounds	0.5 0.1 0.01	37 63 87

Table 4: Impact of different kinds of antibiotics, synthetic chemotherapeutics and disinfection agents on methane formation capacity; © Hilpert 1983.

1.2 TEMPERATURE PROFILES

There are three main defined temperature windows for anaerobic digestion (see Table 5): psychrophilic, mesophilic and thermophilic. These names reflect the type of bacteria associated with the three temperature ranges: different bacteria achieve their maximum productivity within each temperature range. The closer the temperature to the optimum in each range, the better the process.

The higher the temperature, the faster the process, but a faster, hotter process does not lead to the production of more biogas overall (Figure 2). As thermophilic bacteria are more sensitive to temperature fluctuation, they require an effective temperature control mechanism that can maintain an exact temperature. Additionally, these bacteria do not tolerate a high ammonia concentration within the substrate, although they can be gradually adapted to function with increased levels of ammonia.

	Range [°C]	Optimum temperature [°C]
Psychrophile bacteria	15 - 25	
Mesophilic bacteria	30 - 45	38
Thermophilic bacteria	50 - 60	55

Table 5: Temperature zones for bacteria in anaerobic digestion plants; © Paterson 2012, Schulz 2006.

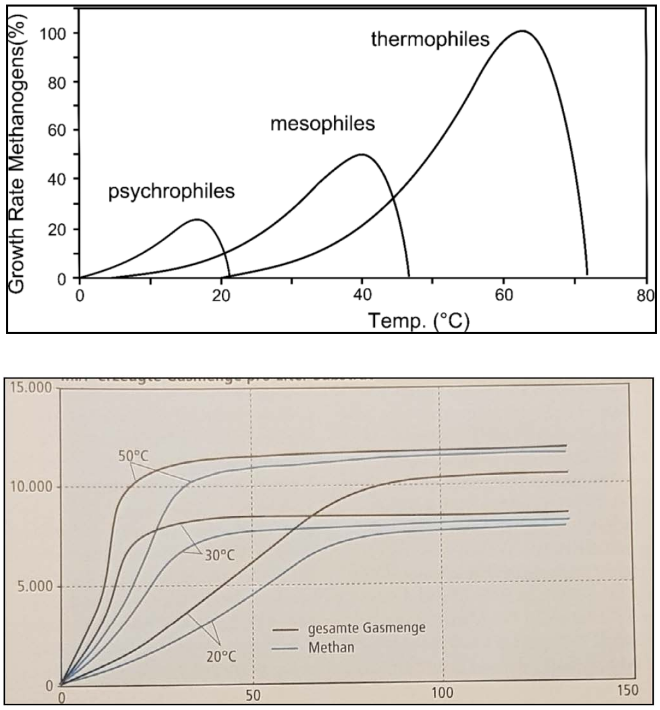


Figure 2: Growth rate of methanogenic bacteria at different temperature profiles and biogas (ml l-1) forming potential depending on temperature and retention time (days); © Baader, Schulz 2006, 1978, Van Lier 1997.

1.3 ORGANIC LOADING RATE AND RETENTION TIME

The chosen temperature range is a major consideration in the design process for a biogas plant; further important factors are the organic loading rate and the retention time of feedstock within the digestion process. The character of the organic matter can differ from year to year, or even between seasons, as well as varying from feedstock to feedstock. It is therefore critical to find the optimum digester size, to ensure that degradable organic matter can completely decompose and maximum biogas yield can be achieved. The organic loading rate (OLR) expresses the weight (in kg) of volatile solids fed into the digester per day and per m³ digester volume. The hydraulic retention time (HRT) shows how long the feedstock will theoretically stay in the digestion process. The HRT is calculated by dividing the daily fed feedstock (expressed in m³) by the active digester volume. Figure 3 shows the link between loading rate and retention time depending on the volatile solid content of the feedstock used.

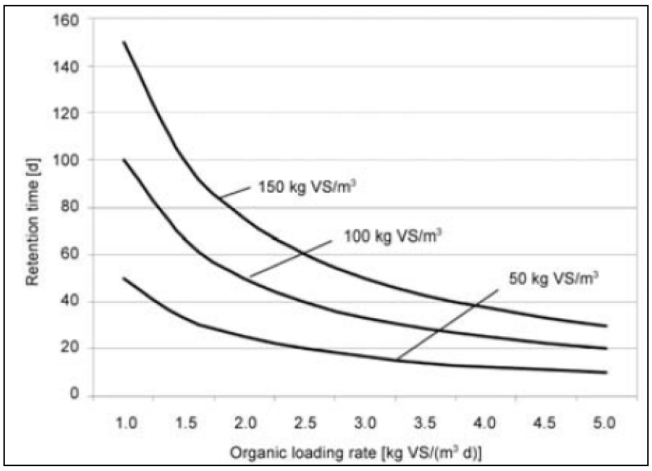


Figure 3: Correlation between organic load rate (OLR) and hydraulic retention time (HRT) depending on volatile solid content of feedstock; © Paterson 2012.

Equation 1: Organic loading rate (OLR): m=amount of substrate expressed in kg per day, c= concentration of volatile solids expressed in %, VR= active digester volume expressed in m³.

$$B_R = \frac{m \times c}{V_R \times 100} \; [kg\ VS\ m^{-3} d^{-1}]$$

Equation 2: Hydraulic retention time (HRT): VR= active digester volume expressed in m³, V= volume of substrate added per day to the digester.

$$HRT = \frac{V_R}{\dot{V}} \; [d]$$

1.4 METHANE PRODUCTIVITY

The productivity of the digester is defined as methane production per m³ digester volume. This figure can only be compared across digestion systems if the same feedstock is used, meaning it is a relatively uncommon equation.

Equation 3: Methane productivity of the digester expressed in $Nm^3\ m^{-3}\ d^{-1}$: $V_{(CH4)}$ = methane production expressed in m³ per day, VR= active digester volume.

$$P_{(CH_4)} = \frac{\dot{V}_{(CH_4)}}{V_R} \; [Nm^3 m^{-3} d^{-1}]$$

Methane productivity, on the other hand, (Equation 4) indicates the methane yield per tonne of volatile solids and is a commonly used parameter.

Equation 4: Methane yield per ton volatile solids expressed in $Nm^3 \, t_{VS}^{-1}$, $V_{(CH4)}$= methane production expressed in m³ per day, m_{Vs}= added volatile solids expressed in ton per day.

$$A_{(CH_4)} = \frac{V_{(CH_4)}}{\dot{m}_{oTS}} \; [Nm^3 t^{-1} VS]$$

Equation 5 provides information about the degradation of volatile organic solids within the digestion process: this means it gives an indication as to the effectiveness of the digestion process.

Equation 5: Degree of degradation of volatile solids expressed in %: VSSub= volatile solids of added fresh mass expressed in $kg_{VS} \, t_{FM}^{-1}$, m_{zu}= mass of added fresh mass expressed in t, VS_{Abl} = volatile solid content of digester discharge expressed in $kg_{VS} \, t_{FM}^{-1}$, m_{Abl} = mass of digestate expressed in t.

$$\eta_{oTS} = \frac{oTS_{Sub} \times m_{zu} - (oTS_{Abl} \times m_{Abl})}{oTS_{Sub} \times m_{zu}} \times 100 \; [\%]$$

1.5 CARBON CONTENT

The composition and yield of raw biogas vary depending on the digestible carbon content of the feedstock. Table 6 and Table 7 give an overview of potential biogas yields from biodegradable components and common substrates used in biogas plants. The figures are an approximate guide, however: biogas yield is heavily dependent on the exact volatile solids content and other factors. For detailed planning with specific feedstocks, in-depth batch analysis is always recommended.

Substance	Biogas yield [Nm^3 biogas kg_{VS}^{-1}]	Methane content [$\%_{Vol.}$]
Digestible carbohydrates	0.79	50
Digestible protein	0.7	71
Digestible fat	1.250	68

Table 6: Specific biogas yields of respective substance groups; © Harasek, 2009, Paterson 2012.

Substrate	TM [%]	Thereof VS [%]	Methane content [%]	Methane yield [Nl_{CH4} kg_{VS}^{-1}]
Manure				
Poultry manure	40	75	55	280
Cattle manure	25	85	55	250
Cattle slurry	10	80	55	210
Pig slurry	6	80	60	250
Energy crops				
Gras silage	35	90	53	320
Fodder beet	16	90	52	360
Cereal silage (whole plant)	35	95	53	330
Green rye silage (whole plant)	25	90	53	320
Closer grass silage (whole plant)	30	90	55	320
Clover alfalfa silage (whole plant)	30	90	55	290
Landscape management gras	50	85	50	100 – 200
Corn silage (whole plant)	35	95	52	340
Sunflower silage (whole plant)	25	90	57	300
Sorghum silage silage (whole plant)	28	90	52	320
Wheat straw	86	90	52	210
Cup plant silage (whole plant)	28	93	58	280
Winter triticale silage (whole plant)	39	95	56	360
Organic waste				
Biowaste	40	50	60	370
Leftovers (kitchen waste)	16	87	60	410
Glycerol	100	99	50	430
Distillers	6	94	55	390
Potato pulp	6	85	54	360

Table 7: Methane yield of different substrate; © Döhler, 2013.

1.6 PLANT DESIGN

The physical characteristics of the feedstocks used will determine the technology required (dry/wet digestion, necessary pre-treatment technologies etc.). The chemical parameters of the feedstock, on the other hand, will determine the amount of biogas produced. The general configuration is usually similar in each biogas plant: plant set-up varies in the details principally because of the different requirements of the substrates used. Differences in design also reflect different requirements for the possible further treatment of the digestate and most importantly, the further application of the biogas produced.

Figure 4 and Figure 5 give an overview of these process steps, which will be described in the following chapters.

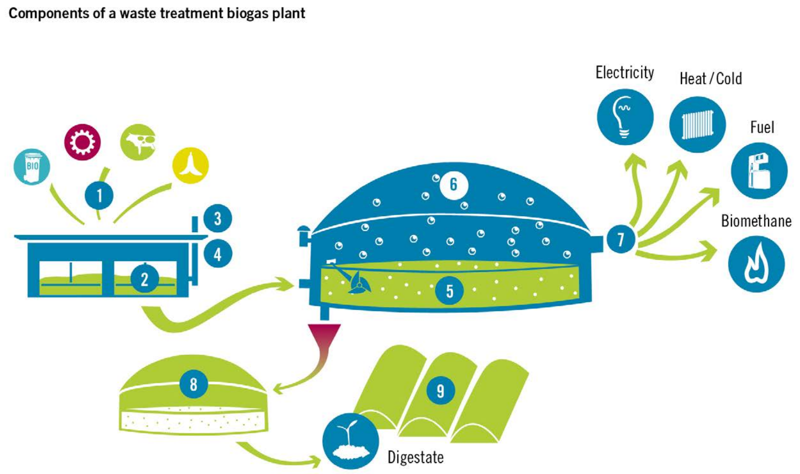


Figure 4: Scheme of a biogas plant 1: different types of feedstock, 2 storage of feedstock, 3+4: air collection and treatment, 5: digester, 6: biogas storage, 7: biogas application, 8+9: digestate storage; © FVB, 2009.

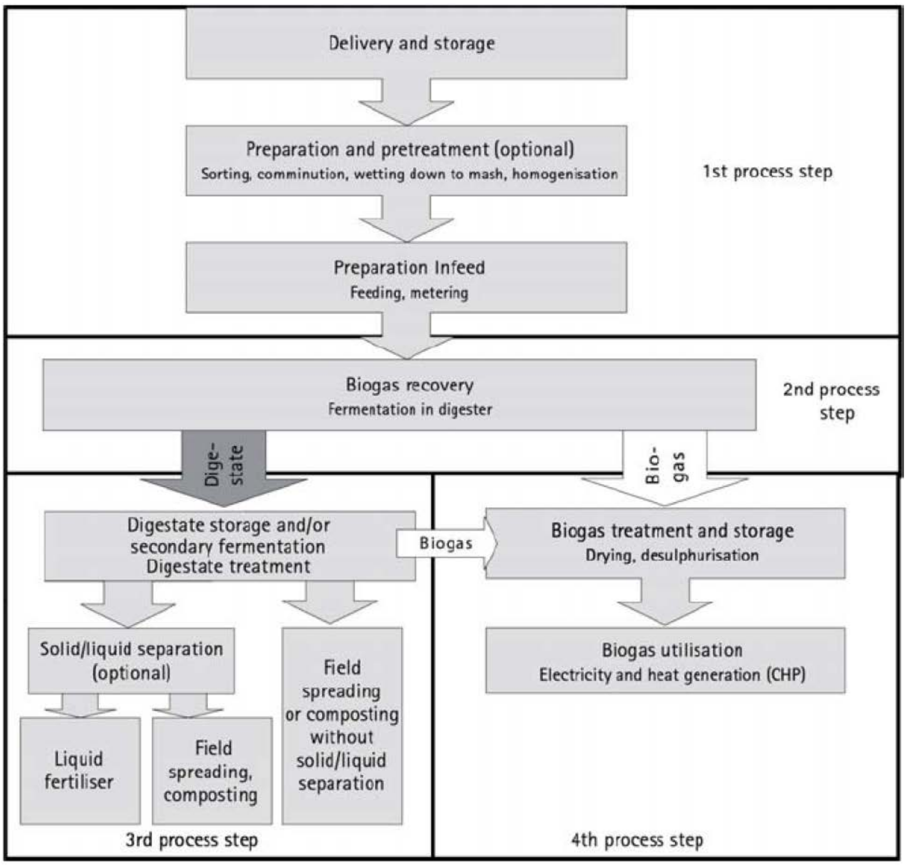


Figure 5: Usual process step of biogas plants; © Paterson, 2012.

2 RECEIPT, STORAGE, PRE-TREATMENT AND HANDLING OF FEEDSTOCK

Each biological process depends not only on the ambient conditions, but also on the feedstock being used. It is therefore very important to quantify and qualify the feedstock. If the feedstock is made up of organic waste from households, catering etc., a pre-check for possible impurities is required in order to ensure that no inhibiting substances enter the digestion process. The following steps are common, although they will vary according to the source of the feedstock:

- Receipt, pre-check and weighing of feedstock
- Pre-treatment
- Storage
- Handling and feeding into the digester

A weighing system and a small office to check the delivered feedstock is usually installed at the biogas plant entrance. In order to determine the amount and quality of the feedstock, the delivered charge is weighed and a sample is taken to measure the dry matter and volatile organic solids content. In some cases, the nutrient content will also be assessed. This data is recorded and used to steer the digestion process. Some plants also take retention samples and store them for further testing or, if problems occur, to carry out a post-check for inhibitors. In general, substrates can be divided into two groups:

a) Substrates which usually have no impurities and are not subject to animal by-product regulation;
b) Substrates which may include impurities (e.g. pathogen bacteria in meat, heavy metals, plastic) and may be subject to animal by-product regulation (1069/2011/EU).

With the exception of manure, agricultural residues belong mainly to group a) and usually accrue in huge amounts during the harvest season. Therefore, different types of storage system are needed. Feedstock can be stored:
- Stacked in steadings and warehouses if dry, bulky and not putrescent (e.g. straw)
- Stored in non-gastight silos or warehouses if dry, not stackable and not putrescent
- Stored in gastight silos if wet, bulky and putrescent or likely to rot. The most common technique to avoid rotting during

storage is to silage the feedstock in vertical or horizontal airtight silos. The preservative might be CO_2 or a reduction of the pH value, depending on the moisture content, the feedstock type and the storage technique used.

- Stored in tanks if liquid and not putrescent

Picture 1: top: office to check delivered feedstock and weighbridge, bottom left: automatic sampling-taking of delivered feedstock, bottom right: batch test determining the methane yield of specific substrates.

Picture 2: Different types of storage systems: top left: not gas-tight silo, top middle: gas-tight silo where conservation is done with carbon dioxide, top right: air-tight silo where conservation is done through lowering pH value, bottom: air-tight clamp silo, where compression is done with heavy machinery like tractors or even snow groomers.

Picture 3: Straw stacked in bales.

Substrates in group b) are generally subject to additional animal by-product regulation and are usually delivered daily. With the exception of manure, group b) substrates can be contaminated with a variety of impurities or even inhibitors. These substrates are therefore subject to completely different requirements on entering the biogas plant.

Feedstock from farms is usually fed directly into the digester on delivery. Only a very short storage time is anticipated for manure, for example. Municipal organic waste is usually stored in waste bins before being collected by special lorries on a weekly basis or in some cases even more frequently. Depending on the collection system, the waste bin will either be cleaned immediately after being emptied into the lorry by the collecting company or it will be transported to the biogas plant, emptied and cleaned there. Despite best efforts in the food supply chain to avoid food waste, food that has passed its expiry date cannot be sold. The best option in this case is to convert the resulting organic waste streams into energy and use the digestate as fertiliser. Companies within the biogas industry have already developed special devices to unpack still-packaged organic waste and separate out packing material or other impurities within one working step. If animal by-products are used as feedstock in the Europe, the sanitation requirements set out in the animal by-product regulations need to be fulfilled. Sanitation is usually carried out immediately on delivery and in most cases the substrate is pumped straight into the digester afterwards.

For substrates that may include impurities or need to be crushed, the separation of any metal fragments or pieces is carried out as a first step. Afterwards, different kinds of devices crush the substrate so that it can be treated more easily and to avoid damage to the plant mechanisms.

Picture 4: Bunker systems for solid organic waste with two different conveying systems, left: screw conveyor, right: crane.

Picture 5: Top left: organic waste bin from catering and households, right: collecting lorry for catering and household waste with integrated emptying and cleaning device, bottom: organic waste bin emptying facility at the biogas plant with a subsequent washing-bay.

Picture 6: Metal separation is always the first step before further treatment, followed by crushing and further separation like sieving, separation through decanter or pulper. Picture source for sieving and pulper; © Sutco Recycling Technik, Lohse Maschinenbau.


Picture 7: Left: unpacking machine for expired food with automatic separation of impurities, right: sanitation devices installed in parallel for higher performance.


Picture 8: Steam explosion, left: continuously processed, right: batch system.

European legal requirements for sanitation of animal by-products (1069/2011/EU, 1009/2019/EU)			
Digestion requirements	**Hydraulic retention time of postdigestion**	**Pasteurization**	**Post composting**
55 °C, > 24 h secured retention time	+ 20 d		
55 °C		+ 70 °C, >1h	
> 37 °C		+ 70 °C, >1h	
> 37 or 55 °C			70 °C + 3 days
> 37 or 55 °C			60 °C + 7 days
> 37 or 55 °C			55 °C + 14 days

Table 8: Possibilities to fulfil legal requirements for animal by-product sanitation of EU Animal by-product regulation and EU fertilizer regulation.

Depending on the properties of the substrate and the digestion system, different mechanisms are used to transport the substrate within the biogas plant until it is fed into the digester. Wheel loaders, self-propelled distribution trailers, screw conveyors, conveyor belts and –if the substrate is liquid–different kinds of pumps are all commonly used to transport substrates from the storage silo into the feeding system.

Picture 9: Self-propelled distribution loader.

Picture 10: Substrate feeder systems for bulky and dry substrates: top left: with internal mixing screws, top right: feeding system with walking floor, bottom left: push floor, bottom right: scraper floor.

Picture 11: The feeding screw must always end below the liquid surface so that no biogas can escape.

Picture 12: Substrate mixing tank followed by a feeding pump.

Picture 13: Pumps with a screw conveyor in front to mix solid and liquid substrate before pumping it into the digester, left: eccentric spiral pump, right: rotary piston pump.

Where dangerous gases or unpleasant odours can occur, rooms must be kept ventilated, or the contaminated air must be collected and cleaned. This is usually done using a biofilter. The collected air is forced into the bottom of the biofilter, where bacteria degrade the odorous substances. Wood chips are usually used as bedding material for the bacteria. In order to ensure correct operation, the temperature, humidity and availability of nutrients in the biofilter must be controlled.

Picture 14: Biofilter filled with wood chip as bedding material for odour substance degrading bacteria.

3 DIGESTER

Although the pre-treatment of the substrates used is a very important step for the performance of anaerobic digestion, the digester is the main technical facility in a biogas plant. Depending on the biological, chemical and technical requirements at each plant, the digestion process carried out can be classified as wet or dry fermentation.

Criterion	Distinguishing characteristics
Wet or dry digestion	Wet digestion Dry digestion
Substrate feed	Intermittent Continuous
Hydraulic flow	Continuously stirred digester Plug flow digester
Process phases (biologically)	Single phase Two phases
Process stages (technically)	Single Two or even multistage
Process temperature	Psychrophilic Mesophilic Thermophilic

Table 9: Classification of the digestion process based on different criteria.

3.1 WET OR DRY FERMENTATION

Irrespective of the distinction between wet and dry fermentation, however, every biological process –including the process of fermentation– requires the presence of water. The greatest material difference between digestion processes therefore lies in the form of the substrate, which can be liquid, solid or even stacked.
There must always be enough water inside the digester for bacteria to be active, even in a dry fermentation process. There is consequently no universal definition of dry fermentation. In some countries, the status of the process as wet or dry fermentation is determined by the water content of the feedstock: if the average dry matter content of the feedstock is above 20 or 25%, for example, the process is classed as dry fermentation.
In other countries, the process is referred to as dry fermentation if the feedstock inside the digester is stackable, for example in dry batch garage systems.

3.2 THE SUBSTRATE FEED: CONTINUOUS AND INTERMITTENT FEEDING SYSTEMS

Most biogas plants are fed continuously, which means several times per day. This helps to maintain relatively constant conditions in the digester tank, which is beneficial for the activity of the microorganisms. The substrate can also be fed into the digester intermittently, or only once a day. This is seldom the case, however, as it interrupts biogas production and could additionally cause process distortions. Some special liquids are fed into the digester continuously. The same volume as is fed into the digester will also be passed out of the digester and on to the next fermentation step, e.g. into the post digester or storage tank, either via controlled pumps or free flow. This keeps the filling level of the digester itself constant and ensures continuous biogas production. Perhaps the least frequently used are garage-type digesters, where stackable feedstock is only fed in in batches, for example, once per month.

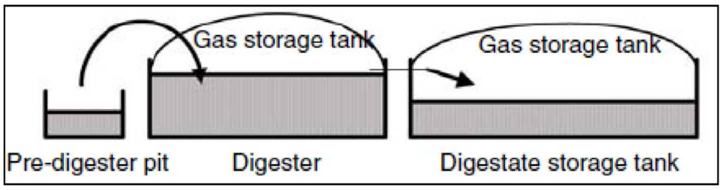


Figure 6: Continuous digestion process called through flow process with a followed gas-tight storage tank; ©FNR,2012.

3.3 THE HYDRAULIC FLOW: CONTINUOUSLY STIRRED, PLUG FLOW DIGESTION, OR BATCH DIGESTER

Most wet digestion systems are continuously stirred (in a **CSTR, or continuously stirred tank reactor**). In these systems, one or more agitators ensure that the substrate inside the digester is in continuous flow so that no separation into floating or sinking layers occurs. This also prevents the occurrence of zones where the temperature gets too low or the acid concentration rises too much. The stirring can be done continuously or semi-continuously. If semi-continuous, stirring at least needs to be carried out often enough to prevent the formation of a floating or sinking layer or problem zone.

A special form of continuously stirred digester is the **hydraulic digester**, in which the stirring is carried out using the gas pressure of the generated biogas. In terms of design, a hydraulic digester usually has a tank-in-tank structure, which is connected at the bottom through concentric openings and at the top through a gas pipe with an automatic valve. Only the inner tank is directly connected to the biogas storage and to the digestate storage tank. When the valve in the connection gas pipe is closed, the generated biogas accumulates and presses the substrate in the outer tank through the opening at the bottom and into the inner tank, so that it and raises the level of substrate in the inner tank. Once the liquid surface in the inner tank reaches a height of about 4m above the liquid surface in the outer tank, the valve is opened, and the fluid levels are immediately equalised through the concentric bottom openings. The substrate is stirred by its movement between the two tanks.

Plug flow digesters are usually lying tanks (round or rectangular) with a horizontal agitator that mixes the substrate but also moves it forward slowly from the inlet to the outlet. There are also vertically installed plug flow digesters in operation. Both horizontal and vertical systems can be operated with dry or wet fermentation processes. In this type of reactor, the different stages of digestion are kept separate from each other, which is an advantage, as the different bacteria groups can all work within their own optimum pH range.

The vertical plug flow system is called UASB digestion (**UASB digestion = upflow anaerobic sludge blanket digestion**). This is a special type of digester which is often installed to reduce chemical oxygen demand in wastewater from industries like dairies, beverage producers and sugar beet factories. It treats rapidly degradable liquid substrates within a retention time that can be as little as one day. The doubling time of methanogenetic archaea is at least 2 days, however, so in order to avoid washing out the last step of the biological digestion process from the digester and causing process disturbances, specially conditioned pellets are filled into the digester where the methanogenetic archaea can settle while the liquid substrate streams upwards and passes them by. The substrate is pumped continuously into the bottom of the digester and flows slowly upwards. At the top of the digester, the biogas produced is collected in special domes.

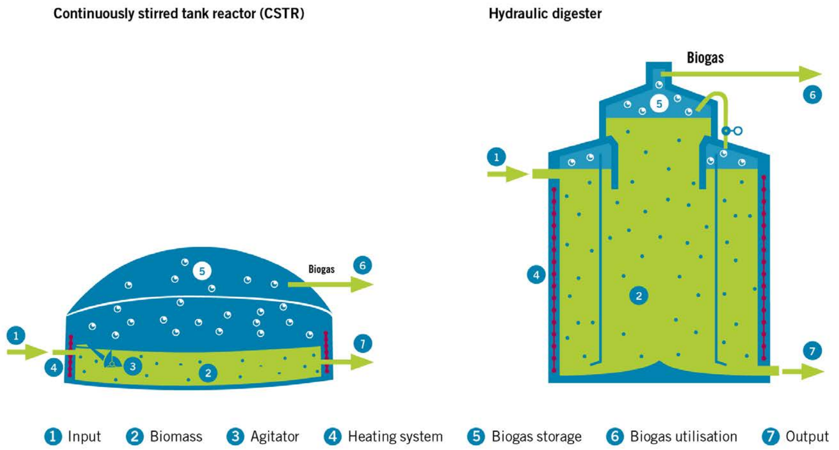


Figure 7: Types of continuously stirred digesters; left: stirred by agitator, right: hydraulically stirred; © FvB, 2017.

Picture 15: Left: Demonstration object of a continuously stirred digester, right CSTR digester.

Picture 16: Hydraulic digester with the higher inner tank and the lower outer tank.

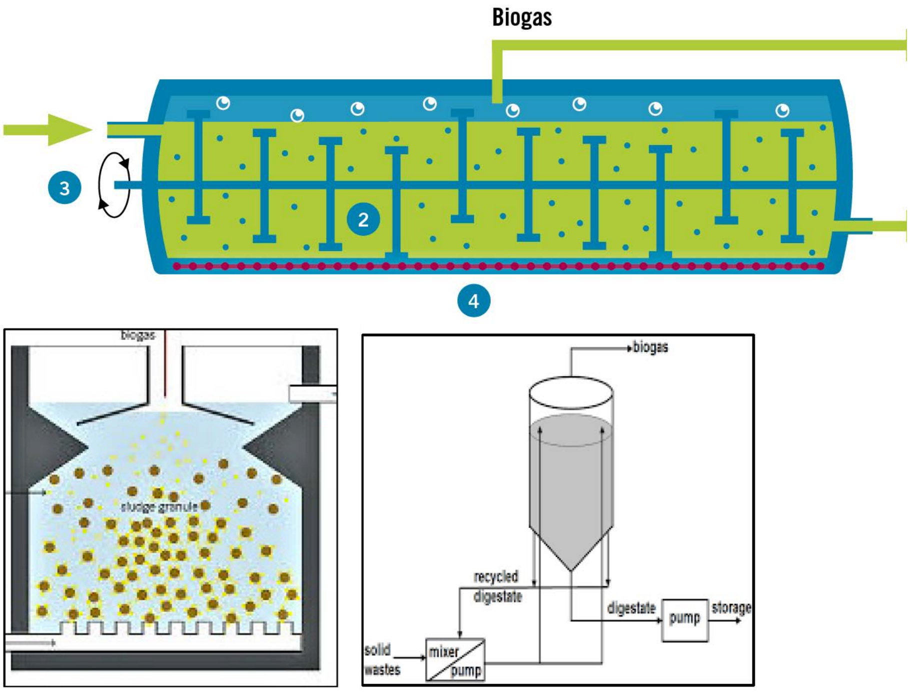


Figure 8: Schemes of horizontal and vertical plug flow digester; top: horizontal plug flow digester with horizontal agitator, bottom left: vertical downstream plug flow dry digester without mixing, bottom right: vertical upstream plug flow digester without stirring.

Picture 17: Top: Horizontal dry digester with horizontal stirring (left round and of steel, right: square and of in situ concrete - digesters in parallel), bottom left: upstream plug flow digester without stirring, bottom right: downstream plug flow digester without stirring (in the background).

Picture 18: Upstream plug flow digester (UASB = up flow anaerobic sludge digester).

Another digester design is the batch dry digester (also called the **garage system**). Here, the substrate is filled into an enclosed space (a garage) which is then sealed airtight. The substrate needs to be stackable and will not be mechanically mixed during the subsequent digestion process. During this digestion process, acid-rich percolate (intercellular water which is released by the feedstock during the digestion process) is collected at the bottom of the digester and pumped to the heated percolate tank, before being pumped and spread from the ceiling onto the substrate. Biogas is usually produced by the stacked substrate and also within the percolate tank. The flow rate can be adjusted in order to determine where most of the methanogenic process takes place. When the substrate is degraded, the digester is aerated and then emptied before being filled with new substrate and starting the process again. The production of biogas using this system is not continuous, so plants using this design usually have several batch digesters installed in parallel, in order to ensure a relatively constnt flow of gas.

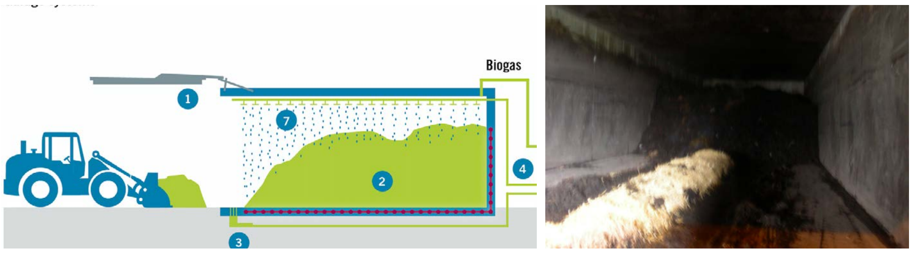


Figure 9: Top: Scheme of a batch dry digester bottom: inside of a batch dry digester; © left Fachverband Biogas 2019.

3.4 BIOLOGICAL PROCESS PHASES: SINGLE-OR TWO-PHASE

Usually, the different steps of the biogas production process takes place simultaneously and is therefore done in one tank. Even if the process is done in more than one digester with the same pH value, this is biologically a single-phase digestion process because all steps of digestion take place simultaneously (see: Figure 1). As the involved hydrolytic and acidification forming bacteria have different requirements compared to methanogenic bacteria on pH value, this can be used to divide the digestion process into two phases:

- Hydrolysis
- Methanization

A separation of these two phases is usually done by lowering the pH value far below 6.5 in the tank where the substrate is fed. The low pH value is achieved by installing a small reactor tank that is operated with a low hydraulic reaction time of only some days and a very high loading rate. By that, the formation of organic acids in the process will lower the pH value. If a low pH value cannot be guaranteed, methane production will usually start and therefore exhaust gas should be collected and connected to the joint gas system of the biogas plant. Because even if the hydrolysis works properly, some hydrogen will be released (besides carbon dioxide) and would cause energy loss if not collected.

Picture 19: Hydrolysis tank upfront of the digester.

3.5 TECHNICAL PROCESS STEPS: MAIN DIGESTER, POST DIGESTER, GASTIGHT STORAGE

Many biogas plants are designed with a main digester, followed by a post digester, followed by a gastight storage tank. These technically distinct process steps are not the same as separating the different biological stages of the digestion process out to create a two- or multi-stage digester. In a single-stage biogas plant with a main digester, post-digester and gas-tight storage tank, the whole biological degradation process occurs simultaneously in each digester, but the design helps to obtain maximum biogas yield and provide a mechanism for dealing with imbalances in the main digester. In a continuously or semi-continuously stirred digester, some substrate leaves the digester before it is fully broken down, meaning that maximum biogas yield cannot be achieved in the main digester alone but requires the addition of a post digester. To ensure that the biogas production process is environmentally friendly, any methane formed in the digestate storage tank should also be collected and used.

Because the substrate is fed first into the main digester, the size and maximum loading rate of this main digester determine the total capacity of the plant. The organic loading rate of the main digester is therefore higher than in the post-digester: this can help to avoid a process distortion, if a substrate is used that may cause disruption. In the event that the process in the main digester is thrown off-kilter by an excessive loading rate, substrate from the post-digester can restore balance and solve the problem. It is important that the temperatures in the main digester and post-digester match, however, otherwise the temperature difference could exacerbate the issue in the main digester, rather than helping to correct it.

Picture 20: Model of a biogas plant with multistage digestion process (feeder, storage tank for slurry, main digester, post digester, gas-tight storage tank.

Picture 21: Typical biogas plant with a main digester followed by a post digester.

3.6 PROCESS TEMPERATURE: PSYCHROPHILIC, MESOPHILIC OR THERMOPHILIC PROCESSES

The biogas process can operate within different temperature ranges:

- Psychrophilic (<25 °C), not very relevant in practice
- Mesophilic (35 - 38 °C), most common temperature range
- Thermophilic (>50 °C), fastest degradation

The higher the temperature, the faster the growth rate of the microorganisms. The mesophilic temperature range is the most commonly used for digestion. Mesophilic operation offers high process stability and a controllable process. The thermophilic process, on the other hand, is more sensitive to process disruption (especially to a higher amount of nitrogen within the substrate) and to temperature fluctuations. In a properly-operated thermophilic process, the digestion is performed faster and the bacteria can gradually adapt to a higher ammonia content. Faster growth and increased activity on the part of the microorganisms mean faster digestion. Consequently, the necessary retention times are lower; the digester can be smaller and can tolerate a faster loading rate while still achieving the same biogas production. In many emerging and developing countries, on the other hand, biogas plants are operated at ambient temperature – for example in the case of lagoons and small-scale domestic biogas plants. The advantage is that no heating system must be installed. The disadvantage is a lower rate of activity among the microorganisms and a likelihood of lower biogas yields. Additionally, larger digesters must be built because if the activity level of the bacteria is low, longer hydraulic retention times are necessary.

Industrial biogas plants usually optimise their operation. To reduce the initial investment requirement and keep a lid on operational and maintenance costs, the digester volumes should be small. Many industrial plants have a heat recovery system with the CHP unit and most prefer mesophilic operation.

3.7 DIGESTER CONSTRUCTION: MATERIALS AND INSULATION OF THE DIGESTER

Locally-produced concrete, steel, enamel or even stainless steel are all common building materials for digester construction. Common steel can be used for digesters if the desulphurisation via oxygen is not carried out in the digester itself as this would lead to corrosion. This means that biogas from digesters made out of common steel always contains H_2S, which needs to be taken into consideration for all equipment used in subsequent applications and process stages. If locally-produced concrete is the building material of choice, the quality of the concrete and of the cement used is very important. In order to ensure the longevity of the plant, the installation of the concrete must be combined with the appropriate post-treatment. For optimal process efficiency, the digesters need to be fully isolated (including the floor) so that every zone of the digester has the same temperature. A fluctuation of as little as 1 °C over a day is enough to have a negative impact on the performance of the bacteria.

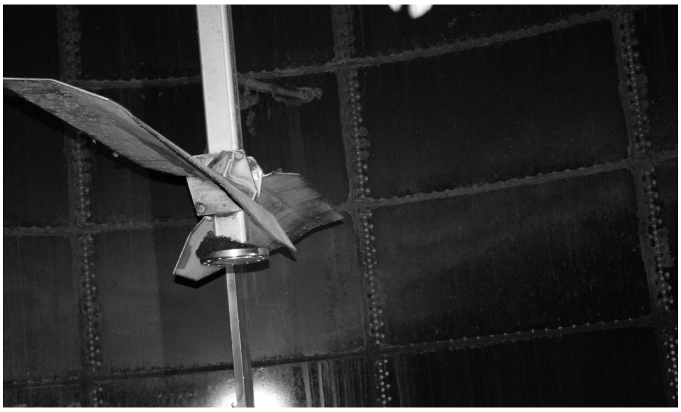
Picture 22: Concrete digester.

Picture 23: Digester material: left: rolled stainless steel digester with floor heating pipes on the outside, right: enamelled steel storage.

Picture 24: Types of wall isolation, top left: special confectioned isolation which is included in the process of casting the concrete, top right: isolation outside of digester through nails, bottom left: sandwich panels, bottom right: isolation under the floor.

3.8 AGITATION

In order to prevent the substrate in the digester from separating out, the majority of digesters (with some notable exceptions, including hydraulic digestors, covered above) need to be stirred by an agitator. Vertical tanks are often stirred continuously by a centrally positioned agitator; other commonly used techniques are propeller agitators (fast or slow running) or paddle agitators.



Picture 25: Vertically central positioned stirrer for a CSTR digester.

Picture 26: Different types of high-speed stirring systems.

Picture 27: Different types of slow speed agitators.

Picture 28: Slow speed agitator in a horizontal digester.

3.9 HEATING

A number of the microorganisms involved in the digestion process are sensitive to temperature changes. Digesters therefore need to be insulated and heated, so as to maintain a constant temperature with temperature fluctuations of less than 1 °C per day. Heating is usually achieved via stainless steel pipes or plastic hoses which are installed inside the digestor (usually against the walls) and thus are in direct contact with the substrate.
In steel digesters, the heating pipes can also be installed between the steel and the insulation layer; similarly, in concrete digestors, the heating pipes can also be built into the the concrete wall. As a further alternative, external heaters can be used. If this approach is adopted, fresh substrate or substrate from the digester is heated in an external heat exchanger.

Picture 29: Heating system with floor heating pipes directly integrated into the concrete wall.

Picture 30: Stainless steel heat pipes directly attached to the digester wall. To avoid corrosion stainless steel pipes need to be installed galvanically isolated.

Picture 31: External heat exchanger where the substrate that will be fed gets heated and pressed into the digester.

4 PUMPS, PIPES, VALVES

In a biogas production unit, pumps, pipes and valves are necessary to transport liquid substances - principally liquid substrates and digestate but also, to a lesser extent, liquid additives. Liquid substrates need to be pumped to the mixing tank and subsequently to the digester. After digestion, the digestate is most often pumped to a digestate storage tank.

This chapter will first discuss the different types of pumps in biogas systems, before examining the requirements for pipes and valves for liquids and offering some examples. Following this, consideration is given to a selection of the most frequently used security and control equipment for pumps, pipes and valves.

4.1 PUMP TYPES

The physical properties of the various substrate types for biogas production can differ enormously. The dry matter content, particle size, temperature, viscosity and nature and amount of possible impurities in the substrate all vary. To handle the wide range of different liquid substrates used for biogas production as well as the different stages of fermentation, a range of pump types is available. Even so, the preliminary removal of stones and other impurities can be necessary to facilitate pumping. Concentrated substrates can also be diluted to allow them to be pumped smoothly. Four different types of pump often used at biogas facilities are discussed below: rotary pumps, rotary displacement pumps, cavity pumps and peristaltic pumps. In practice, the pumps used in biogas plants are often of a similar kind to those used for liquid manure pumping.

Despite precautionary measures and good substrate pretreatment, pumps can clog and need efficient clearing and regular maintenance. It is therefore recommended that pumps should be installed in readily accessible positions, with sufficient working space around and about them. Pumps can be controlled by timers and/or process-controlled by a control system (control of power consumption, pressure measurement at input and output side, flow rate metering etc.). In this way the process can be either fully or partially automated. In some cases, the transport of liquids within the biogas plant is handled in its entirety by one or two pumps, centrally situated in a pump station or control cabin. The piping is routed in such a way that all operations are controlled by means of readily accessible or automatic valves.

Pumps can be divided into self-priming and non-self-priming pumps. A self-priming pump is capable of evacuating any air which it has taken in and return to normal pumping. This capability means the pump can be installed above the liquid level and the liquid can be drawn along a suction pipe. Pumps which are not self-priming, in contrast, must be situated below the liquid level. Of the pumps described below, rotary pumps are not self-priming, whereas the different types of positive displacement pumps (rotary displacement pumps, cavity pumps and peristaltic pumps) are self-priming.

4.1.1 ROTARY PUMPS

Rotary pumps are commonplace in liquid-manure pumping and eminently suitable for runny substrates (those with a dry matter content below 8%). A rotary pump is composed of an impeller turning inside a fixed body. The impeller accelerates the liquid and the resulting increase in flow velocity is converted into pressure at the rotary pump's outlet. The shape and size of the impeller can vary, depending on the properties of the liquid. Rotary pumps are simple, compact and robust in design and have a high delivery rate. They are not suitable for liquid metering.

Picture 32: Impeller of rotary pump.

Picture 33: Rotary pumps.

4.1.2 POSITIVE DISPLACEMENT PUMPS

A positive displacement pump makes a fluid move by trapping a fixed amount of liquid and forcing this fixed amount into the discharge pipe. Since the amount of liquid trapped is the same each time, the volume pumped in each cycle of operation is also consistent and the pump theoretically produces a constant flow at a given speed. This makes positive displacement pumps suitable for liquid metering. This type of pump is used to pump semi-liquid substrates with high dry matter content. Positive displacement pumps are relatively susceptible to disruptive substances, meaning that they require good pretreatment processes and thorough removal of impurities from the substrate prior to pumping. The most frequently used types of positive displacement pumps at biogas facilities are rotary displacement pumps, cavity pumps and peristaltic pumps.

4.1.3 ROTARY DISPLACEMENT PUMPS

Rotary displacement pumps have two counter-rotating rotary pistons with between two and six lobes in an oval cavity. The two pistons counter-rotate and counter-roll with low axial and radial clearance, touching neither each other nor the body of the pump. Their geometry is such that in every position a seal is maintained between the suction side and the discharge side. Figure 10 illustrates the principle of a rotary displacement pump.

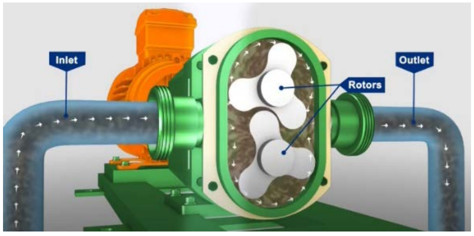


Figure 10: Rotary displacement pump.

Picture 34: Left: piston of a rotary displacement pump, Right: Damaged piston through impurities like stones.

4.1.4 CAVITY PUMPS

A progressive cavity pump consists of a helical rotor and a stator. According to the geometry of the rotor and the stator, sealed fixed-size cavities between suction and discharge are formed. The cavities move when the rotor is rotated but their shape and volume do not change. The pumped material is moved inside the cavities. The opening and closing of these cavities create a depression in the suction nozzle, which causes the fluid to be sucked in and develops a volumetric flow directly proportional to the rotation of the rotor. Figure 11 shows the working principles of a progressive cavity pump. For cavity pumps, it is especially important to provide enough space in front of the pump to pull out the rotor when maintenance is required.

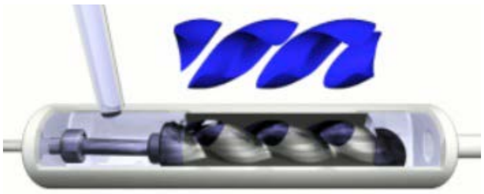


Figure 11: Cavity pump.

Picture 35: Cavity pump.

4.1.5 PERISTALTIC PUMPS

In a peristaltic pump, the fluid is contained within a flexible tube fitted inside a circular pump casing. A rotor with a number of lobes rotates in the pump casing, such that the lobes push against and compress the flexible tube as they go round. This forces the fluid to move along the tube, a bit like squeezing toothpaste out of a toothpaste tube. The same principle allows fish to be pumped without being squashed. The working principles of a peristaltic pump are shown in Figure 12.

Picture 36: Peristaltic pump.

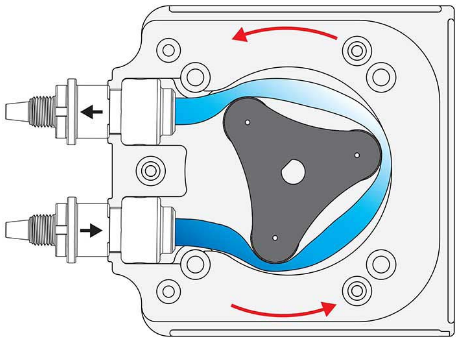


Figure 12: Peristaltic pump.

4.2 PIPES AND VALVES FOR LIQUIDS

The pipes and valves discussed in this subchapter are those used for transporting liquids in the biogas plant. Valves prevent the unwanted flow of liquids, for example from the digester to the pre-digester pit or between digesters. In order to comply with safety

requirements, double valves are sometimes installed, so that there is a second valve that can be closed if the main valve leaks.
The pipe materials most often used are PVC, HDPE, steel or special steel, depending on the substance to be piped, temperature and pressure level. Most valves are made of stainless steel.

Some important requirements for liquid-carrying pipes and valves are listed below.

- Piping, valves and fittings must be contents-proof, temperature-proof and corrosion-resistant.
- Valves and fittings must be readily accessible and operable.
- They must be installed in such a way as to be protected from frost damage.
- Suitable insulation must be fitted for handling warm liquids.
- All materials must be chemically resistant to the liquid being piped and must be rated for maximum pump pressure at a given temperature.
- Piping must be routed to prevent backflow of the liquid e.g. from the digester to the pre-digester pit.
- Cast iron piping is not considered a good choice because the formation of deposits is more of an issue than in smooth-surfaced pipes made of materials such as plastic.
- Pipes below the surface should be monitored for leakage

Examples

- **Gate valves**

A gate valve is a valve that opens by lifting a barrier (gate) out of the path of the fluid. Gate valves require very little space in the pipe and do not significantly restrict the flow of liquid when the gate is fully opened. Gate valves are generally installed upstream of each flap trap, for example. A flap trap is a trap with a hinged flap that permits flow in one direction only, thus preventing backflow. A gate valve is necessary to prevent backflow if interfering substances prevent the flap trap from closing correctly. Gate valves can also be installed as shut-off valves, allowing pumps to be isolated from the piping system.

- **Manual vs. automatic valves**

While manual valves are operated by a qualified person, automatic valves can be remotely controlled by an automated computerised control system. Automatic valves have additional control devices installed which check the actual position of the valve, to make sure it is correct . These two types of valve differ considerably in their design and operational functions.

4.3 SECURITY AND CONTROL EQUIPMENT FOR PUMPS, PIPES, AND VALVES

Picture 37: Rotary displacement pump with manually steered (left) and automatically steered (right) valve(s).

Pumps can be controlled by timers and/or process-controlled by a control system. If a timer is used, a computer will turn the pump on and off at predetermined times. Alternatively, or in addition, a control system can be installed. This usually consists of pressure sensors and/or flow rate measuring. The sensors monitor the pressure and flow rate of the liquid before and after it passes through the installed pump; the values obtained are then compared with the desired or optimum value programmed into the computer, so that the control system can adjust the pump speed in order to achieve the desired conditions. Using a control system, the process can be either fully or partially automated. As well as controlling pump speed, pressure sensors before and after the pump are installed to check for vacuum formation (before the pump) or excessive pressure (after the pump), in order to detect maloperation and thus avoid damage to pumps, pipes and valves.

The pumping demand, or the rate at which the pump is required to work, is often recorded and shown on a graph. A significantly elevated pumping demand may be due to worn pumping parts such as the rotor or stator from a cavity pump; however, it can also be caused by a raised viscosity of the pumped liquid, the installation of an oversized impeller in a rotary pump, or contact between rotating parts and stationary parts, to give a few examples.

Picture 38: Rotatry pistion pump with rubber puffer on both sides to avoid vibration damage and pressure measurement devices before and after to detect vacuum or too high pressure.

5 GAS COMPRESSION DEVICES, PIPES, VALVES

5.1 INTRODUCTION

In a biogas production unit, gas compression devices, pipes and valves are primarily used to transport the biogas produced. They are also required for double membrane gas storage systems and for oxygen supply, in cases where the desulphurisation of the biogas is carried out via oxygen injection (further information in chapter 10). The piping systems connect all digesters in which biogas is produced with biogas appliances such as the CHP unit or the biogas upgrading unit, as well as the biogas storage system. This chapter examines two types of gas compression device – one which is used for biogas compression to transport the biogas to the utilisation facility and one used in double membrane gas storage systems. Following this, an overview is provided of the main requirements for gas-carrying pipes and valves.

5.2 TYPES OF GAS COMPRESSION DEVICE

Depending on the requisite flow and pressure, the following types of gas compression device are most frequently used for biogas compression: radial fan, piston compressor and screw compressor.

5.2.1 RADIAL FAN

A radial fan, also known as a centrifugal fan, moves the biogas or another gas in a direction at a 90-degree angle to the incoming gas and thus changes the direction of the gas flow. The fan has the shape of a drum with an output duct. The propeller inside the drum accelerates the gas flow and the duct sends the outgoing gas in a specific direction. Radial fans are constant-displacement or constant-volume devices, meaning that, at a constant fan speed, the fan moves a relatively constant volume of gas.

Picture 39: Radial fan.

5.2.2 POSITIVE DISPLACEMENT COMPRESSOR

Positive displacement compressors work in much the same way as positive displacement pumps (chapter 4). The biogas or another gas is drawn into one or more compression chambers, which are then closed from the inlet. Gradually, the volume of each chamber decreases, and the gas is compressed internally. When the pressure has reached the desired value, a port or valve opens, and the gas is discharged into the outlet system. The most frequently used positive displacement compressors at biogas facilities are piston compressors and screw compressors.

5.2.3 PISTON COMPRESSOR

A piston compressor uses pistons driven by a crankshaft to deliver gases at high pressure. The crankshaft is a rotating shaft which converts its rotating motion into a repetitive linear motion of the pistons (illustrated in Figure 13). During the backward motion of the piston, the inlet valve is opened and the gas is sucked into the compression chamber. Next, the piston moves forward in the same compression chamber; when the gas has reached the required pressure, the outlet valve is opened and the gas is pushed out of the compression chamber.

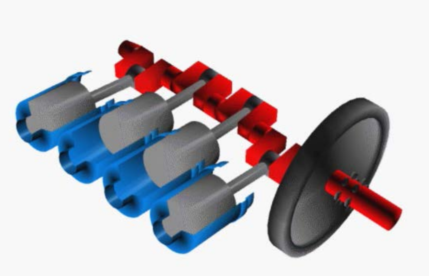
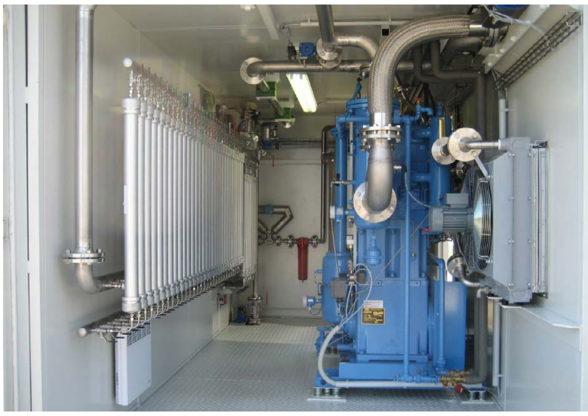


Figure 13: Illustration of the working principle of a piston compression.



Picture 40: Piston compressor (right) with membrane upgrading system (left).

5.2.4 SCREW COMPRESSOR

A screw compressor uses a rotary working principle. Gas is sucked in through an intake port, compressed between two rotating screws and released through the outlet port. They are often used to replace piston compressors where large volumes of gas must be compressed or high pressures are required.

5.3 USE OF GAS COMPRESSION DEVICES

5.3.1 BIOGAS COMPRESSION

Biogas is not typically produced a constant rate; its quality can be inconsistent and it will not necessarily be generated in the exact amounts and at the exact rate required by the utilisation facility (CHP, upgrading unit or other device). Gas storage systems help to accommodate fluctuations in the process.

Gas compression devices are used to transport the biogas from the biogas storage to the utilisation facilities much as pumps are used to transport liquids. The compression device can both "pull" the biogas from the storage and "push" the biogas towards the utilisation appliance. The biogas is delivered at constant pressure to the gas utilisation facilty.

The operating gas pressure in most anaerobic digesters is low (only a few mbar) while the gas utilisation unit is usually constructed to operate at a higher pressure. In addition, the transport of biogas along piping entails pressure loss. Compression devices for biogas are therefore needed to deliver the biogas at the higher pressure required by the gas utilisation unit.

5.3.2 DOUBLE MEMBRANE GAS STORAGE

Storage of the biogas produced is required in order to provide temporary buffering and accommodate fluctuations in gas production. Biogas can be stored in the digester itself or alternatively, when more storage capacity is required, in a separate gas holder (Figure 14). Both types of storage often work with double membranes, meaning two membranes lying one inside the other. The external membrane is maintained in a stable form. It is brought into its shape with the use of a gas compression device which blows air between both membranes. The outer membrane together with the air blown between both membranes serve as a protector for the inner membrane against the influence of environmental factors such as wind and snow. The biogas is stored within the inner membrane. In this scenario, the gas compression device is not transporting biogas but is instead blowing air to facilitate safe biogas storage.

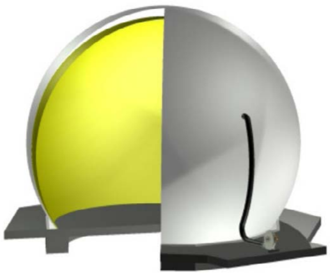


Figure 14: Double membrane gas holder.

Usually, the volume of the gas storage is determined by the gas usage. If the gas is utilised in base load operation (e.g. about 8000 h/a CHP operation) the storage capacity might be around 4-8 hours of biogas production. If the lplant requires flexible operation (e.g. a CHP plant that depends on the fluctuating demand in the electricity grid), the gas storage might be bigger, perhaps holding about 8-12h biogas production. In nearly all cases, the dimensions of the gas storage system are calculated to balance demand and consumption on a daily basis and not to compensate for seasonal variations.

5.4 PIPES AND VALVES FOR GASES

This subchapter examines the pipes and valves used to transport gases (biogas and biomethane) throughout the biogas plant. Galvanised steel (G.I.) or polyvinyl chloride (PVC) are the most commonly used materials for this purpose.
The requirements for biogas piping, valves and accessories are mostly the same as for other gas installations. Some important requirements for pipes and valves for (bio)gases are listed below:

- Biogas is saturated with water vapour. It contains hydrogen sulphide and other corrosive components. Consequently, no piping and valves that contain any amount of ferrous metal may be used for biogas piping, because they would corrode very quickly.
- The piping systems need to be safe and economical and should allow the required gas flow for the gas appliance in question.
- The piping systems must remain reliably gastight for the lifespan of the biogas unit. In the past, faulty piping systems were the most frequent cause of gas losses in biogas plants.
- All parts of the piping system above ground must be resistant to environmental damage such as UV, heat and fracturing. For this reason, galvanised steel pipes are recommended above ground, rather than PVC pipes, which are not recommended and often not permitted for use in exposed settings.
- When placing pipes underground, the bottom of the pipe-laying cavity must be well compacted before the pipework is installed. All pipework should be free of stresses and strains. If necessary, bellows adaptors or U-bends should be included.
- Once the piping is installed, it must be tested for possible gas leakage.
- All valves, fittings and pipes must be suitably protected against frost.
- As biogas is saturated with water, there will be condensation if it cools down in the pipes. Gas-carrying pipes must therefore be installed with enough of a downhill gradient (1-2%) to ensure that condensate, slight settling, or sag cannot produce unintended high points in the network that might impede the flow of gas. Because the biogas can travel through the system at relatively low pressures, small quantities of condensate can be enough to cause a complete blockage. The piping system

must be equipped with condensate traps which allow water to be extracted from the system.

- All valves must be readily accessible, easily serviced and easy to operate.

Examples

As far as possible, cock or ball valves suitable for gas installations should be used to provide a shut-off and isolating mechanism within the gas pipe network. Shut-off valves allow cleaning and maintenance work to be carried out without the need to close the main gas valve. The most reliable valves are chrome-plated ball valves. Gate valves of the type normally used for liquids are not suitable.

- **Ball valves**

A ball valve consists of a valve casing containing a rotatable ball to control flow. It uses a full port (full bore) or reduced port (reduced bore) mechanism. A port or bore is a cylindrical flow passage through the centre of the ball: when this passage is aligned with the casing and the pipe, the gas flows through; if the ball is rotated by 90% then the passage is no longer in alignment and the flow stops. In a full port or full bore ball valve, the diameter of the hole in the ball is equal to the pipeline diameter so that, when open, the valve offers little or no restriction to the gas flow. In a reduced port or reduced bore ball valve, the diameter of the hole in the ball is smaller than that of the pipe and so the valve absorbs a small amount of pressure drop.

Figure 15: Ball valve.

- **Cock valves**

Cock valves have a similar working principle to ball valves. Instead of a ball, they use a tapered plug with a through-port (or hole) in the middle. If the port is aligned with the valve and the pipe, gas will be able to flow through; if the plug is rotated by 90 degrees, so that the port is perpendicular to the pipe and the valve, the gas flow will stop.

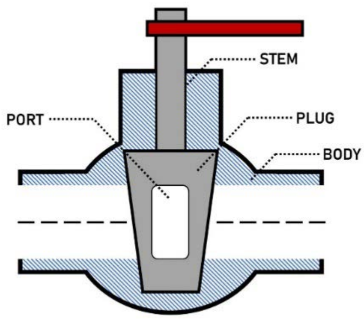


Figure 16: Cock valve.

6 SAFETY EQUIPMENT

The production of biogas is a complex engineering process which involves working with highly flammable gases and other hazards. As long as the adequate safety measures are taken to reduce all potential risks, however, the biogas plant can be operated safely. It is important to consider safety measures during the planning phase as well as during the whole process of biogas production. This chapter describes the main hazards present in a biogas plant and the basic equipment that any biogas plant requires in order to be operated safely.

6.1 OVERVIEW ON ENVIRONMENTAL AND HEALTH RISKS IN A BIOGAS PLANT

Before we analyse the safety equipment necessary in a biogas plant, it is important to understand the main potential risks of the biogas production process. Biogas is produced through the breakdown of organic matter by bacteria that metabolise the organics and release a range of gases. This process is called anaerobic digestion (AD). The exact makeup of the biogas obtained varies hugely depending on the feedstock used and the digestion temperature; the main components of biogas, however, are methane (50 – 75 %) and carbon dioxide (25 – 50 %). It also contains impurities, such as hydrogen sulphide, ammonia and other gases, again to varying degrees depending on the feedstock and the way in which the digestion process is set up.

The presence of some of these gases in biogas facilities entails potential **risks for the environment**, as shown in table 10. Methane is a particularly potent greenhouse gas (GHG); hydrogen sulphide can be highly toxic for both animals and humans; and ammonia can cause water contamination.

In addition, some of the gases present in the biogas production process represent a **health risk for humans**, including injury from potential explosions, suffocation and exposure to poisonous gas hazards.

Typical health risks for humans are:

- Mechanical hazards (which are by far the most frequently-occurring hazards),
- Hazardous substances
- Explosion hazards
- Fire hazards
- Electrical hazards

Table 10 below shows the ranges of ignition, flame propagation speed in the air and explosion for biogas and methane compared to natural gas, propane and hydrogen.

	Biogas (60% CH_4)	Natural gas	Propane	Methane	Hydrogen
Heating value (kWh/m^3)	6	10	26	10	3
Density (kg/m^3)	1.2	0.7	2.01	0.72	0.09
Density relative to air	0.9	0.54	1.51	0.55	0.07
Ignition temperature (°C)	700	650	470	595	585
Max. flame propagation speed in air (m/s)	0.25	0.39	0.42	0.47	0.43
Explosive range (% v/v)	6 - 22	4.4 - 15	1.7 - 10.9	4.4 - 16.5	4 - 77
Theoretical air consumption (m^3/m^3)	5.7	9.5	23.9	9.5	2.4

Table 10: Properties of various gases. Source: SVLFG, 2016.

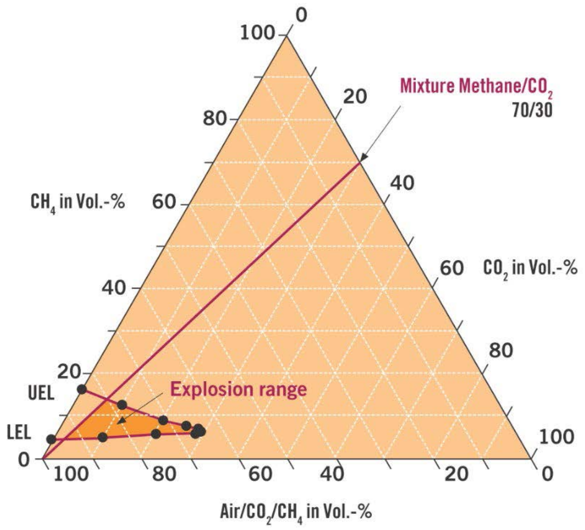


Figure 17: Explosion triangle for biogas. Source: UEL: Upper Explosive limit, LEL: Lower Explosive Level, German Biogas Association/GIZ.

The concentration of the different gases present in biogas facilities must be monitored constantly. Table 11 sets out the properties of the main gases present in biogas facilities and the main health and environmental hazards these entail (see next page).

Substance	Properties	Health risks	Environmental risks
Methane (CH_4)	• Odourless gas. • Lighter than air, will collect toward upper spaces.	• Explosive at 5% to 15% concentrations. • In a confined space, it creates an oxygen-deficient atmosphere and can cause suffocation.	Methane leakage: methane is a particularly potent greenhouse gas (GHG)
Carbon dioxide (CO_2)	• Odourless gas • Heavier than air, tends to accumulate in low-lying areas.	• High concentrations can cause unconsciousness and death.	
Hydrogen sulphide (H_2S)	• It smells like rotten eggs. • Heavier than air.	• At very low levels can irritate eyes, nose, throat and respiratory system. • High concentrations destroy the sense of smell and can cause inability to breathe, extremely rapid unconsciousness and death. • Highly flammable gas.	High (short-term) toxicity to aquatic life, birds, and other animals.
Ammonia (NH_3)	• Pungent odour. • Lighter than air.	• Inhalation of lower concentrations can cause coughing, and nose and throat irritation. • Exposure to high concentrations causes can result in blindness, lung damage or death.	Water contamination.

Table 11: Main gases present in biogas facilities. Source: EBA.

Further risks are presented by the use of mechanical and electrical equipment at the biogas plant. Appropriate training for operators and adequate maintenance procedures are key to avoiding any hazards that might arise during operation of the equipment.

The infographic below shows the different hazards that may occur in a biogas plant, divided into 5 different categories:

- Hazardous substances
- Explosion hazards
- Fire hazards
- Electrical hazards
- Mechanical hazards

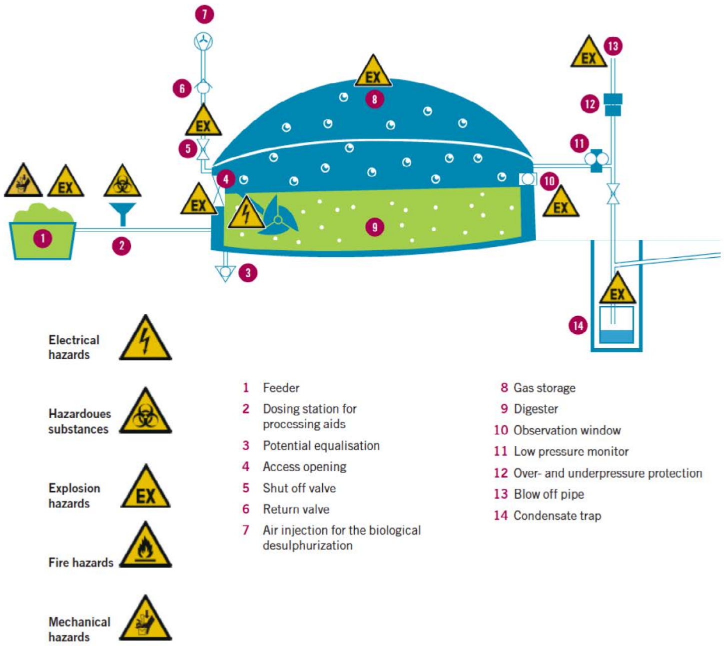


Figure 18: Hazards we can find in a biogas plant. Source: German Biogas Association (FvB).

6.2 SAFETY EQUIPMENT

Safety equipment helps avoid damage to the installations and reduce the risk of accidents involving the personnel working at the plant. It can be divided into:

- Installed devices: control system, over/under pressure device, flare and fixed gas warning systems.
- Portable devices: gas detectors and personal protective equipment (PPE).

6.2.1 INSTALLED DEVICES

Installed devices prevent the pressure from becoming too low or too high within the airtight systems of the biogas plant. If excessive pressure is detected in the airtight gas system, a flare burns the excess biogas to prevent an explosion and avoid methane emissions into the air[1]. Gas warning systems signal spaces with a gas concentration risk.

CONTROL SYSTEM

The optimisation and control of biogas plants is challenging because anaerobic digestion (AD) is a combination of physical, chemical and biological processes. AD takes place in an airtight container, the digester, in the absence of oxygen and at a standard temperature of between 38 °C and 55 °C.

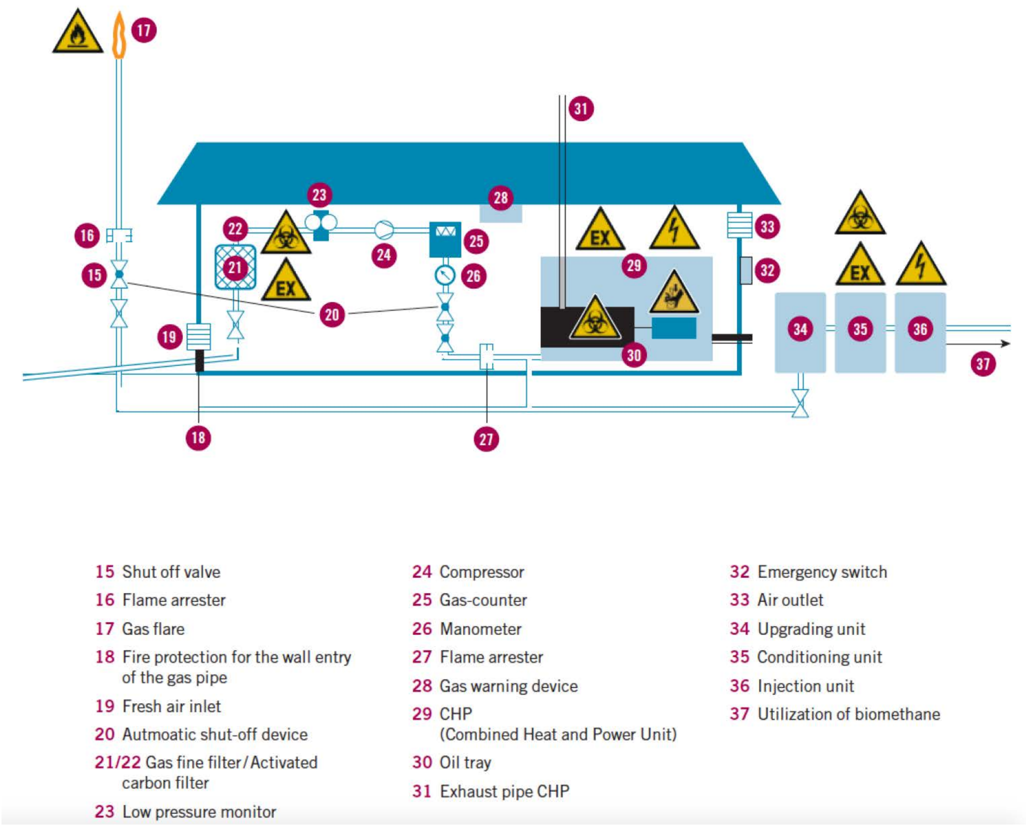


Figure 19: Hazards we can find in a CHP station. Source: German Biogas Association (FvB).

The process is affected by external factors, such as local weather conditions, environmental changes and variations in the daily feed load. It is therefore critical to monitor the AD process as closely as possible, to facilitate the detection of unstable process states. It is important to remember that the main work in the digester is carried out by microorganisms. The living conditions for these living organisms must be as optimised as far as possible, which means keeping a close eye on any changes to the conditions occuring during the AD process (due to feedstock, temperature variations, pH values etc.). Careful monitoring and steering of the process parameters is essential for optimal biogas plant operation.

Plant operators can use predictive models to help them stabilise the fermentation that takes place in the digester during the AD process and give them more control over the biogas output.

In all digestion tanks, a fill level monitoring system must ensure that the fill level is not exceeded.

In the event of low pressure:
If the quantity of substrate removed exceeds the volume of gas generated, the pressure in the tank will drop and the system may be damaged. If this happens, the digestion tank is sealed off from the gas collection system. Following this, the under-pressure protection device would be triggered, and an alarm signal would warn about under-pressure in the tank.

In the event of excessive pressure:
If the production rate of the biogas is higher than its rate of use and the storage capacity is limited, the pressure is likely to rise, which could damage the system. Biogas production can be reduced by lowering the input of feedstock, which should have an impact oin the production level within a matter of hours. This should be done in any case before the gas storage system reaches 100% capacity. However, if there is an excess of pressure in the gas system, a gas-consuming facility (e.g. gas flare, boiler, CHP) should prevent the uncontrolled release of biogas. If the pressure is high in spite of these measures, the over pressure valve will open to protect the plant from damage. Because this releases untreated biogas into the atmosphere, it should be viewed as a last resort.

Chronological sequence of measures to avoid excess pressure:

1. Reduce or even stop feeding;
2. Start all biogas consuming devices;
3. Activation of biogas flare;
4. Opening of over-pressure valve.

OVER AND UNDER PRESSURE DEVICES

It is important to monitor over- and under-pressure in the airtight tanks that contain biogas. The over- and under-pressure valve is an essential safety component of a biogas plant: it is designed to prevent the pressure of the gas contained in the airtight tank from exceeding or falling below set limits.
In the event of over-pressure, the excess amount of gas has to be released and safely discharged. If there is a significant drop in pressure, the system must safely compensate for the drop by allowing outside air to flow in until the pressure returns to a safe level.

Picture 41: Over and under pressure valve. Important to notice that exhaust pipe must be outside.

Picture 42: types of over and under pressure valves, Important to notice: no valve has to be installed between valve and digester, exhaust pipe has to be outside of contact area, if installed outside it needs to be secured from freezing.

It is also important to monitor over- and under-pressure in the airtight gas system as a whole, including gas storage, pipes, etc. If excess pressure is present in the system, an alternative gas-consuming facility (e.g. gas flare) should prevent the uncontrolled release of biogas (see next section).

It is also important to monitor over and under pressure in the overall airtight gas system, which includes gas storage, pipes, etc. If overpressure is present in the system an alternative gas-consuming facility (e.g. gas flare) should prevent the uncontrolled release of biogas (see next section).

FLARE

Biogas flares are used to safely burn biogas that is surplus to the demand of the energy recovery plant or is left unused due to a recovery plant failure. The gas flare system must meet the general requirements for plant components exposed to gas. It must be gastight, corrosion-resistant and frost-proof. The gas flare system is usually driven by the fill level of the gas storage, either pressure-controlled or via an external signal. Every gas flare system must have a safety valve that prevents the uncontrolled flow of air into the gas system of the biogas plant.

Picture 43: Enclosed flare in biogas plant.

There are different types of flare, which can be divided into two main categories:

- Open flares
- Enclosed flares

Open flares are quite simple and consist of a burner from which the flame is protected by a small windshield. The simplicity of the system results in relatively low costs, but on the other hand, the combustion process is more difficult to control. Due to the severe heat loss, these flares must be elevated a number of meters above the ground to protect workers and pipework.
Enclosed flares are usually located on the ground. The burner is protected by a cylindrical enclosure of refractory material; because this isolates the flame, the combustion process is more controlled and emissions are lower. These flares include control equipment which makes it possible to flare gases with different compositions and flows. Enclosed flares burn at a higher temperature and are designed to keep the gas burning inside the chimney for a specific amount of time (residence time) in order to ensure the complete destruction of any toxic elements contained within the biogas.

GAS WARNING SYSTEMS

Constant monitoring of the work environment is key to ensuring the early detection of gas in hazardous areas, in order to prevent or contain damage. The fast and reliable detection of leakages is facilitated by placing fixed gas warning systems close to possible gas release sources.

These devices are used to measure hazardous concentrations of specific gases, notably:

- H_2S, which can be highly toxic for humans
- CH_4, as it is a highly explosive gas
- O_2 and CO_2, to prevent the risk of suffocation

In these systems, the gas sensors are connected to a control system to monitor and process the data received. They are used to detect flammable or toxic gases andoxygen depletion. Even the smallest gas leak will trigger an alarm to prevent operators working in the affected area. Written operating instructions must be available covering the actions to be taken if the alarm is triggered by the gas-warning device or in the event of interruptions to the function of the gas-warning device.

The location of these devices must be carefully assessed before their installation, with consideration given to all elements that could interfere with an accurate reading on the sensor, such as gas weight or air flow. In addition, gas warning systems must be appropriately calibrated, wired and maintained.

Fixed installed devices are connected to the control unit and will sound an alarm if the lower explosive level (LEL) is reached; at the same time, ventilation of the area in question should start operating at maximum capacity. If the upper explosive limit (UEL) is reached, the control unit seals the area to biogas; all electric devices in the affected space should be shut down and current should be disconnected. Entry to the area is then only granted to specially equipped teams.

6.2.2 PORTABLE DEVICES

GAS DETECTORS

Explosion, suffocation and poisonous gas hazards may be detected using portable gas devices. These devices are used as personal equipment and carried by staff to evaluate the potential presence of flammable or toxic concentrations of methane, carbon dioxide or hydrogen sulphide and measure oxygen levels. They can be calibrated to detect specific concentrations of gas at only a few parts-per-million, which are undetectable without specialised equipment.

Picture 44: Portable gas detector.

These devices are either hand-held or worn on clothing or on a belt/harness and they are usually battery operated. They transmit warnings via audible and visible signals.

As we saw previously, gases such as methane and carbon dioxide are odourless and a high concentration of hydrogen sulphide can immediately neutralise the sense of smell. This can be extremely hazardous to the human body, as these gases have explosive and asphyxiating properties. Having equipment on hand to detect such gases is essential for the safety of the plant, and most importantly, the workers. Only qualified people should use these sensors to determine if an area is safe.

As a preventative measure, plant operators must not enter a facility where there may be a dangerous concentration of gas. Natural ventilation cannot be trusted to dilute the explosion hazard sufficiently. Some of the gases produced are heavier than air and tend to accumulate close to the floor.

If a dangerous atmosphere is detected, the area must be cleared immediately and the written safety instructions in the operation manual must be followed. Such incidents must also be recorded in the operating logbook.

PERSONAL PROTECTIVE EQUIPMENT

When recommended by the relevant safety instructions, personnel working in a biogas plant must wear protective equipment to avoid direct exposure to toxic and flammable gases. If a member of staff enters a zone with a hazardous concentration of gases, they need to wear a gas detection device and measure gas concentrations before entering the area in question. When entering without a gas detection device, they must wear adequate clothing and use non-sparking equipment.

In addition, specific cleaning routines must be observed. These include washing hands before going for breaks and upon completion of work, as well as regular cleaning and ventilation of the workplace, as well as cleaning of work clothing and personal protective equipment.

Employees must also avoid eating or drinking at workplaces where there is a risk of contamination by biological agents. Smoking is forbidden throughout the whole biogas plant site. Open flames or sparks are not allowed near the digester and next to electrical equipment, due to the risk of combustion. External visitors must receive the relevant safety instructions when entering the plant.

Figure 20 below illustrates the items of personal protective equipment (PPE) to be used in a biogas plant. Each of these items offers protection against one or more hazards. They must only be worn when a member of staff is directly exposed to a specific hazard.

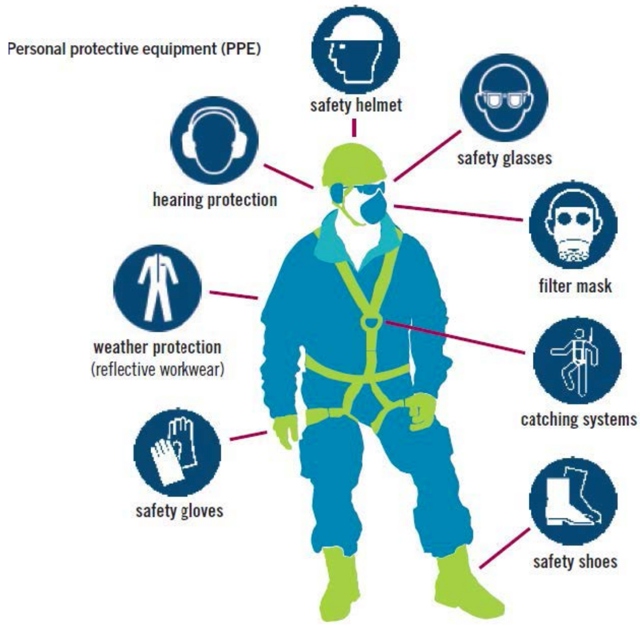


Figure 20: Personal Protective Equipment (PPE). Source: German Biogas Association (FvB).

7 MCR: MEASUREMENT, CONTROL AND REGULATION TECHNOLOGY

One of the most important tools in facilitating highly efficient biogas processes is measurement, control and regulation technology (MCR). This is the central unit in a biogas plant, where all measured data are brought together, recorded and checked, and which sounds an alert if data values are not within the specified parameters. The following data are usually measured:

- Weight of feedstock within the feeding system and fed into the digester
- Pumped quantities (from slurry tanks into the digester, between digesters and digestate delivery, liquid additives)
- Liquid level within the digesters (sensors are located at the top and the bottom)
- Temperature within digesters (sensors are at the bottom and close to the surface of the liquid)
- Filling level of the biogas storage tank
- Biogas production, amount, rate (m³ per time unit) and composition (CH_4, CO_2, H_2S, H)
- Actual electricity consumption of agitators
- Lower explosion limit in rooms where gas pipes are installed
- Energy consumption (electricity, heat)
- Energy production (electricity, heat, biomethane)
- CH_4 and in some cases H_2S in rooms where biogas may occur.
- Pressure inside the digester

The permission-issuing authority often requires the measurement of CH_4 and H_2S in rooms where biogas might occur, meaning this is obligatory in most biogas plants. The other data categories listed above are not always measured in all biogas installations. In most cases, the bigger a biogas plant is, the more parameters are measured. This is because bigger biogas plants require a higher level of initial investment and the additional outlay needed for measuring equipment is low relative to the overall financial input.

The measured data is recorded and analysed; with an interface, the data can be stored externally and is generally used for further evaluations. More and more facilities in a biogas plant are now steered automatically using an MCR unit. Some sections of the plant, such as the CHP, the biogas upgrading unit, the biogas analysis and the feedstock feeder, always have their own process control system to steer their function internally. These are connected via interfaces to the main MCR unit and can also be steered from there. For some devices, such as the feeder, pumps and agitators, it is beneficial to have the main steering buttons directly to hand in the location where the device is situated. MCR technology can also be remotely controlled so that the main process parameters and functions can be monitored and steered from outside the plant.

7.1 MEASUREMENT OF PROCESS PARAMETERS

Anaerobic digestion is a biological process; it is challenging to steer it so that it operates in a consistently efficient way and at maximum productivity. Several research programmes have been carried out to determine the absolute characteristics and limit values of an ideal process. Measuring the pH value is easy but takes some time and therefore does not give feedback about process disturbances early enough. Each biogas plant develops its own adjusted biocenosis and has its own composition of volatile fatty acids. This means it is perfectly possible that, of two plants with the same concentration of volatile fatty acids, one will operate at full capacity and perform well, whereas the other could face huge biological problems.
Nevertheless, the fatty acid concentration is one of the main factors in process disturbances. It is not only the content of fatty acid that is significant, but also the changes in the fatty acid concentration over time.

Unfortunately, the measurement of fatty acids cannot yet be done online (except by using a gas chromatograph, which is too expensive for this purpose) and instead needs to be carried out in a laboratory, on site or externally. Many operators send samples to external laboratories multiple times a year, for analysis of the fatty acid content. This is often done in conjunction with feedstock analysis, as well as nutrient and micronutrient content analysis. A high total volatile fatty acid (VFA) content suggests the possible inhibition of methanogenic archaea. A further rise in the VFA content would cause the pH value to drop. These conditions would not inhibit the growth of the hydrolytic and acidogenic bacteria, which would continue to increase, but the activity of the methanogenic archaea would stop at low pH values. This would give rise to, a negative cycle, in which the hydrolytic and acidogenic bacteria produce even more organic acids, which further lowers the pH value, which in turn further inhibits the activities of the archaea. The total volatile fatty acid content should therefore not exceed 4 g l^{-1} (acetic acid equivalent). An optimal pattern for VFA includes a higher concentration of shorter chain VFA (acetic acid, propionic acid) and a lower concentration of longer chain acids. If the concentration of longer chain VFA rises relative to the acetic acid level, the process may be inhibited. (Herrmann C. 2020, Kaiser F. 2010).

Proposed upper limits for fatty acids		[mg l^{-1}]
Acetic acid equivalent		4 000
From that	Acetic acid	3 000
	Propionic acid	1 000
	Butyric acid	600
Proportion between acetic acid and propionic acid should be 2:1.		

Table 12: Proposed upper limits for fatty acid content; © Henkelmann 2010, Kaiser 2011.

As the substrate used in biogas plants usually has a high buffer capacity, the measurement of volatile fatty acids alone may not give enough information to evaluate the digestion process. The higher the buffer capacity, the longer the pH value will remain constant, even though the acid concentration is rising, and the process may continue to run effectively. Several studies have been carried out to find an easier and even more precise diagnostic method to determine process stability. In the end, a method known as FOS/TAC was developed. It is the quotient of volatile fatty acid concentration (expressed in mg l^{-1} acetic acid equivalent) divided by the total inorganic carbon (expressed in mg_{CaCO3} l^{-1}). Several companies offer special kits for establishing the FOS/TAC value. Values around 0.4 are fine. Values above 0.8 indicate process disturbances and should be acted upon by reducing or even stopping the feed into the digester until the reason for the process distortion is found and fixed. The effectiveness of this method is still under discussion, however, and again these values cannot be seen as absolute because each plant has its own biocenosis.

7.2 MEASUREMENT OF FOAM

Another effect that can be very disruptive to the performance of the biogas plant is the formation of foam on the substrate surface inside the digester. There are numerous factors which can cause this to happen: a change to a high-energy, rapidly-degradable feedstock; a lack of micronutrients; temperature fluctuations; and a number of process inhibitions by surface active agents (tensides); all of these issues and more may give rise to a build-up of surface foam. If the formation of the foam cannot be stopped immediately, it frequently leads to an almost complete standstill of the biogas production process. Because foam may get into gas pipes etc., there is also a risk of secondary damage. If protein-rich feedstocks with the potential to cause foam are used, an ultrasonic surface monitoring system should be installed, the micronutrient content should be checked more frequently, the feeding should be done hourly and other technical disturbances, such as temperature fluctuations, should be avoided. If foam still occurs, one of the fastest countermeasures is to stop feeding, start stirring, lower the filling level within the digester and pump in digested substrate from the post digester or from the storage tank. If the latter is done, care must be taken not to change the temperature within the digester as this would cause further process inhibition. Anti-foaming agents can also be used; however, it is important that these do not lead to the formation of siloxane (Kliche, 2017).

7.3 MEASUREMENT OF THE GAS, QUALITY AND QUANTITY

The quality of the gas says much about the stability and health of the biological process and of course about the energy produced. All biogas plants are therefore equipped with a device that analyses gas. It shows the composition of the biogas and gives information about the following:

- CH_4 – the most valuable component. The higher the CH_4 content, the more energy is in the gas.
- CO_2 – the balance between CH_4 and CO_2 is important in determining the stability of the biological process. The CH_4 concentration should be higher than the CO_2 concentration; changes in this balance indicate unstable process conditions.
- O_2 – indicates the likelihood of leaks in the gas system. If O_2 is above 1%, the operator should check for leakage.
- H_2S – toxic and corrosive gas. Can occur in concentrations, from under 100 ppm up to several thousand ppm (mainly depending on the quality of the feedstock). Levels of H_2S should be as low as possible. In most cases, the technical equipment defines safe limits for H_2S; for CHP operation, this is typically in the range of 50 - 200 ppm.
- H_2 – measurement for process optimisation.

Excursus: the measurement of hydrogen

Information about process stability can be derived from the measurement of hydrogen. Hydrogen, acetic acid and carbon dioxide are the molecules from which biogas is made. An increasing hydrogen content is an early indicator of process distortion (BMWFW, 2017): it suggests that the methanogenetic process is hindered while the first steps of biomass degradation are as yet undisturbed. This would result in ongoing acid production without the acids being transformed into methane and so the pH value would then start to drop. Checking the hydrogen content in the biogas is one of the most sensitive ways of monitoring for possible process disturbances. As with other biological processes, it is not the total amount of hydrogen which is the indicator, but any sudden changes.

FLOW METER

The flow meter measures the volume rate of biogas production, typically in m^3/h. This value also shows whether the biological process is stable. If the rate of production drops, the living conditions for the microorganisms are not optimal anymore and measures to stabilise the process must be taken.
The biogas production rate also indicates whether the biogas plant as a whole is operating in an efficient manner and whether the gas yield matches projections for the feedstock used.

7.4 DOCUMENTATION OF DATA

Data recording has become more and more important in recent years, not least due to legal requirements. Many of the legal institutions that are responsible for granting permission to build or for the regular inspection of biogas plants require data to be recorded and regular internal audits to be carried out, as well as and professional external audits.

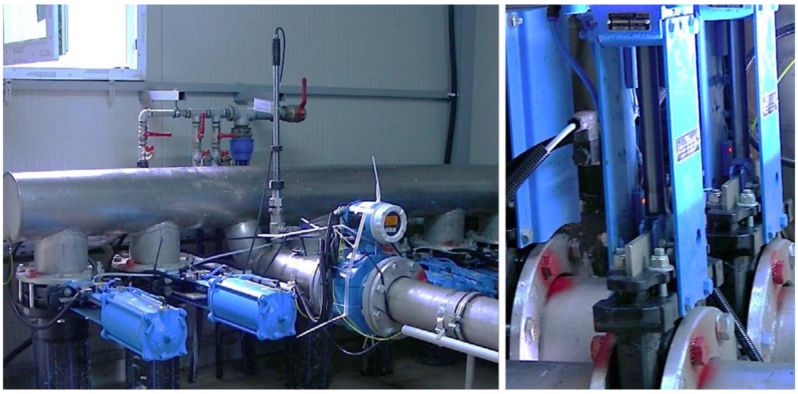
Keeping a record of checks on safety devices, maintenance carried out and professional external audits has become more and more important.

Data measured by the MCR equipment are automatically recorded, but all other record-keeping must be done in a separate logbook. Some MCR systems can also be set up to include these data or at least to provide a reminder when new data are due.
The photographs below show examples of MCR technology.

Picture 45: Feeder for bulky substrates with included weighing unit and big display also directly on the device so staff has control when loading the feeder.

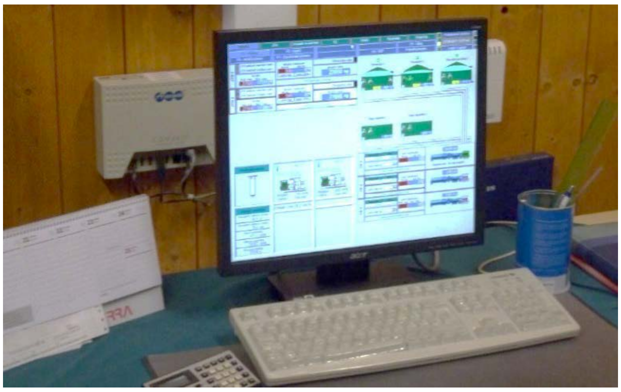
Picture 46: Measurement devices for temperature and level sensors (right: ultrasonic measures from top).

Picture 47: Pumping station with pressure sensor before and after the pump to detect distortions.



Picture 48: Flow meter and contacts within valves giving the actual status of the valves.

Picture 49: Biogas analysis to detect CH_4, CO_2 , H_2S and H.



Picture 50: Visualization of the MCR.

Figure 21: left: inspection hole with camera system, right: manual inspection.

8 DIGESTATE STORAGE AND USE

The most recognised product of anaerobic digestion is biogas. The secondary product, digestate (the effluent of a biogas plant), is also very valuable, however. One of the most significant aspects of AD is that it combine renewable energy production with nutrient recycling. Biogas consists mainly of methane, carbon dioxide and very low amounts of hydrogen sulphide and nitrogen. This means that only carbon, hydrogen and oxygen, along with small traces of other substances, leave the biogas system as biogas. Nearly all nutrients from the feedstock remain in the digestate: the digestate includes almost all nutrients that came into the process with the feedstock and it can be thought of as a full compound organic fertiliser. Depending on the feedstock used, considerable amounts of carbon which cannot be degraded and formed into biogas may also remain in the digestate. Examples include lignin and celluloses, which biogas plants degrade only partially or not at all, and which therefore remain in the digestate. These residual amounts of carbon are valuable sources for humus formation on arable land.

To give an example of a nutrient saved via the biogas production process - phosphorous is one of the essential macronutrients for plant growth and is seen as a finite resource. It is already perceived as a critical raw material (COM/2017/490 final), but still gets lost via the disposal of all kinds of organic waste streams and sewage sludge in incinerators and landfill sites. This loss of phosphorous will only gain importance in the future. At the beginning of the last decade, the European Union started a process streamlining the legal situation of nutrients from organics, in order to support nutrient recycling from organic streams.

Thanks to an amendment, digestate is now included in the EU fertiliser regulation (2019/1009/EG) and is set to become an EU fertilising product that could then be sold across borders within the EU without any further restrictions. Significantly, the moment digestate becomes a fertilising product under EU fertiliser regulation, it automatically ceases to be considered as waste (Article 19). Furthermore, the specific rules governing animal by-products in Article 46 state that digestate produced from animal by-product feedstocks is no longer considered an animal by-product. An amendment to Annex V of the REACH regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals, 1907/2006/EG) has also been made, clarifying that digestate no longer has to

be registered under REACH(Article 12 of Annex V).
An advantage of the use of digestate as fertiliser is that the farmer can reduce the money spent for synthetic mineral fertiliser and/ or can expect higher crop yields if digestate is used. The following example might illustrate this advantage: the development of biogas plants in the 1970s and 80s (before renewable energy production was supported by national governments) was mainly driven by European organic farmers. They were not allowed to use synthetic mineral fertiliser on their farms, but by operating a biogas plant, they produced their own fertiliser and achieved higher crop yields. Producing fertiliser may be a huge motivation for many farmers. This aspect is very important, especially in low fertilising systems, which are very common in developing counties.

8.1 PROPERTIES AND INGREDIENTS OF DIGESTATE

The quality of digestate can vary significantly according to the feedstock used and the choice of digesting technology. The following table shows the main characteristics of raw digestate from some example analyses.

	unit	n	10% quantile	arithmetic average	90% quantile
DM content	[%]	2137	2.8	5.8	9.1
organic matter in DM	[% of DM]	1926	55.2	68.9	82.2
pH value		1922	7.5	7.9	8.3
N total	[% of DM]	1857	4.9	10.4	17.8
NH_4-N	[% of DM]	2058	1.7	6.4	13.1
K_2O	[% of DM]	1513	2.0	5.1	8.3
P_2O_5	[% of DM]	1520	1.7	3.7	5.5
CaO	[% of DM]	1180	2.1	4.7	8.0
Mg	[% of DM]	1179	0.3	0.7	1.3
Cr	[mg/kg DM]	1128	6.5	15.8	26.8
Cd	[mg/kg DM]	1102	0.2	0.4	0.6
Pb	[mg/kg DM]	1118	2.2	6.9	11.2
Zn	[mg/kg DM]	1133	160.0	332.0	530.0
Cu	[mg/kg DM]	1134	35.0	94.7	177.7
Hg	[mg/kg DM]	1098	0.0	0.1	0.2

Table 13: Main properties and ingredients of raw digestate from energy crops, manure and biowaste (© Kirchmeyr 2016).

In terms of plant nutrition it is makes a difference whether the nutrients are bound in the solid material of digestate or available relatively quickly because they are already in the liquid phase. The next Figure 22 gives the relevant information and shows that some elements are mainly dissolved in the liquid (like K) while others (like P) occur principally in the solid phase of the digestate.

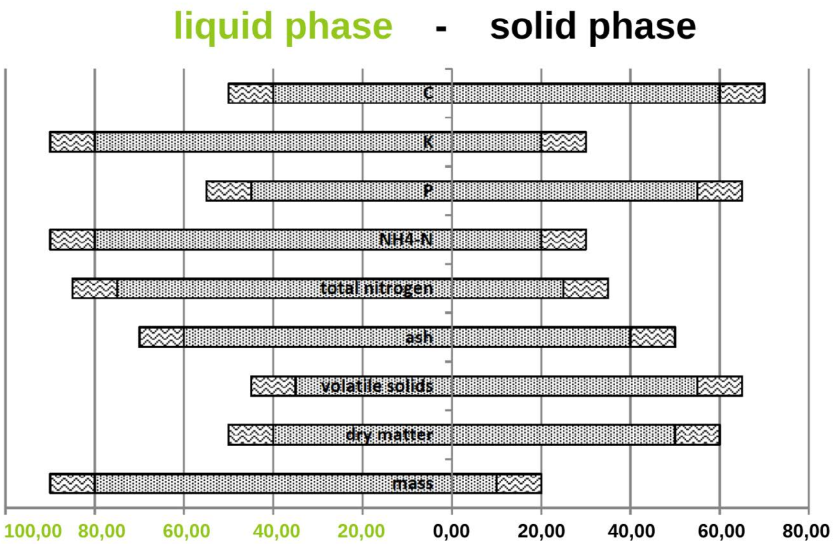


Figure 22: Distribution of nutrients and other relevant parameters between liquid and solid phase of raw digestate [%]; © Fuchs 2010.

Digestate can be further treated, or technically upgraded, Making it possible to produce concentrated fertiliser, which is easier to transport. The liquid and solid phases can also be separated, so that the liquid phase can be spread on the fields while the solid phase is composted. To date, the most common techniques used to upgrade digestate are the screw press or the decanter; these are the most developed, reliable and cost effectivetechniques currently available. Due to the growing average size of biogas plants in Europe, as well as the increasing number of plants and the significant efforts being made to achieve a circular economy, a new generation of upgrading techniques is now being developed.

	unit	n	10% quantile	arithmetic average	90% quantile
DM content	[%]	205	1.5	5.4	9.2
organic matter in % DM	[%]	173	53.7	65.9	77.6
pH value		157	7.6	7.9	8.3
N total	[% of DM]	186	5.9	13.1	22.0
NH4-N	[% of DM]	183	2.8	8.0	15.7
K2O	[% of DM]	177	4.5	15.9	12.9
P2O5	[% of DM]	177	1.0	3.2	4.5
CaO	[% of DM]	141	2.3	5.1	8.0
Mg	[% of DM]	146	0.4	1.2	1.6
Cr	[mg/kg DM]	119	2.9	12.3	29.6
Cd	[mg/kg DM]	117	0.2	0.4	0.7
Pb	[mg/kg DM]	118	1.0	7.8	18.6
Zn	[mg/kg DM]	121	137.0	361.0	556.0
Cu	[mg/kg DM]	121	27.8	90.8	202.0
Hg	[mg/kg DM]	117	0.0	0.1	0.2

Table 14: Main properties and ingredients of liquid fraction of treated digestate from energy crops, manure and biowaste; © Kirchmeyr, 2016.

Further information about digestate, digestate use and digestate upgrading can be found in the publication 'Digestate as Fertiliser' produced by the German Biogas Association in 2018 (Fachverband Biogas).

8.2 HYGIENIC BENEFITS OF DIGESTATE

Early in the development of the biogas market in Europe, the possibility was raised that digestate used as fertiliser might cause cross-contamination of different kinds of diseases. Because many biogas plants are operated in an agricultural setting, it became evident that there is a strong need for scientific clarification on this issue. In a similar way, concern was voiced as to whether weed seeds, unwanted plant propagules from weeds and plant pathogens could be brought into the digestion process via the energy crops used – straw, crop residues, vegetable waste etc.. In order to clarify whether weed seeds, plant propagules or plant pathogens can pass through the digestion process without losing their germination or sprouting ability, several studies were carried out (e.g. by Leonhardt et al. 2010). The results showed that a proper digestion process destroys unwanted weed seeds, plant propagules and plant pathogens. For example, their survey shows that even bitter dock (Rumex obtusifolius) – one of the most feared weed seeds in agriculture – has only 14% germinability left after a three-day digestion process at 35 °C and is destroyed after a retention time of seven days. In short, the study demonstrates that with a properly controlled digestion process (with a retention time over 7 days and a digestion temperature of at least 35 °C), the germinability of weed seeds is no longer a problem.

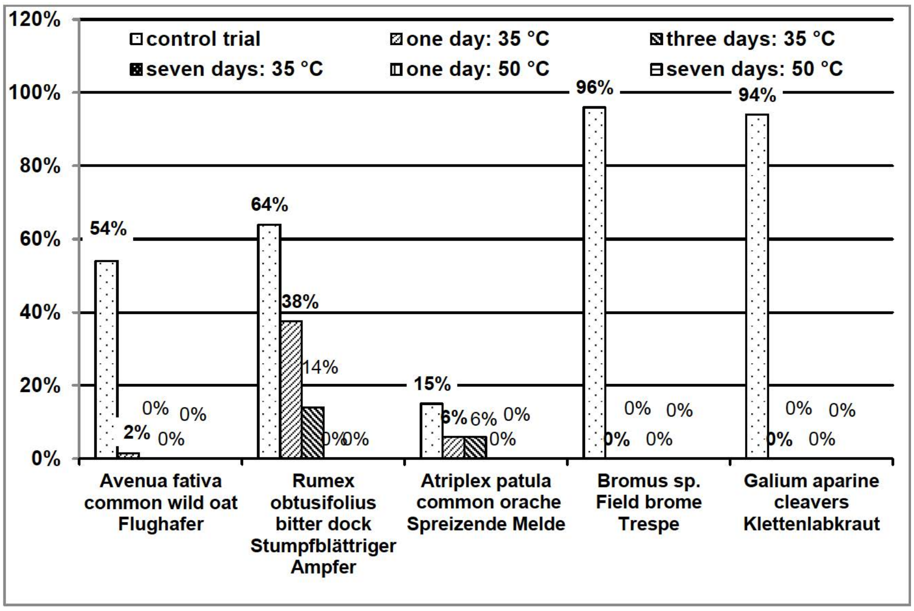


Figure 23: Germination ability of different kinds of weed seeds by 35 °C and 50 °C digesting temperature and depending on the retention time; © Pfundtner 2010.

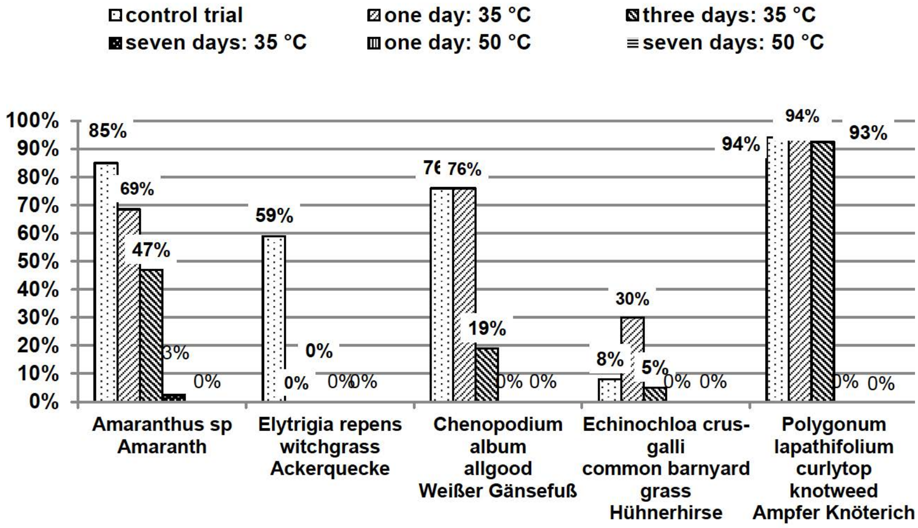


Figure 24: Germination ability of different kinds of weed seeds by 35 °C and 50 °C digesting temperature and depending on the retention times; © Pfundtner 2010.

To give an example: in recent years, Europe has faced an invasion of new plants that have completely overrun existing railroad embankment and other extensively used land. Two of these invasive new plants, Japanese knotweed (Reynoutria japonica) and yellow nutsedge (Cyperus esculentus), were examined with regards to their behavior after digestion. Plant propagules from the Japanese knotweed lost their viability after 7 days at 37 °C. Seeds from the yellow nutsedge lost their germinability after 21 days at 37 °C or 7 days at 55 °C (Fuchs, 2017).

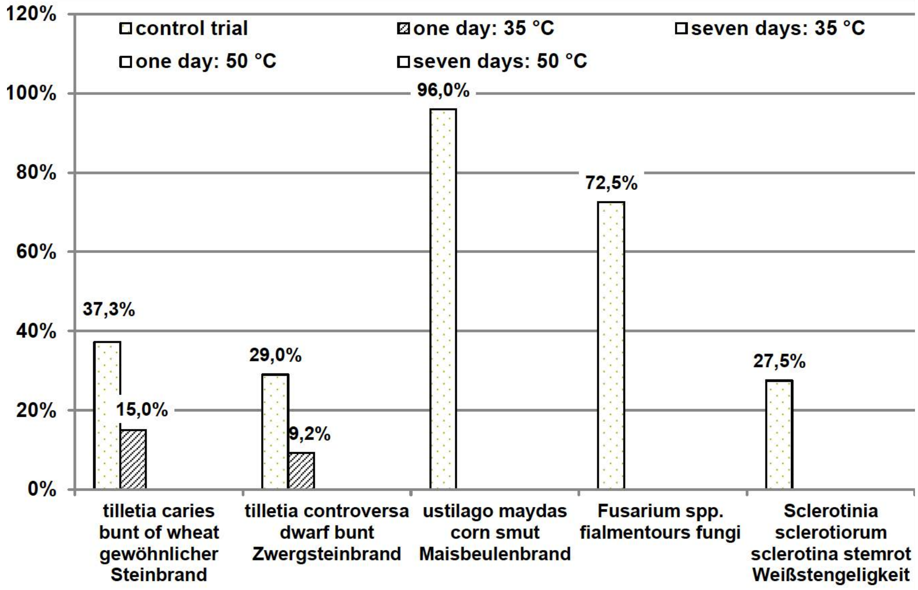


Figure 25: Viability of different types of pathogens in digesters operated by 35 °C and 50 °C after a one-day and seven-day retention time; © Pfundtner, 2010.

In the same report, the Austrian Agency for Health and Food Safety (Österreichische Agentur für Gesundheit und Ernährungssicherheit GmbH, or AGES) investigated the viability of plant diseases such as corn smut, fusarium, common bunt of wheat, sclerotinia and dwarf bunt. All of them lost their viability within one week when the digestion temperature was at least 35 °C.

A further, much-discussed topic is the viability of pathogens, because biogas plants are designed to offer the best growing conditions for bacteria and archaea. IEA task 37 put together a brochure specifically on this topic by pulling together the conclusions of several studies. The results (summarised by Lukehurst, Frost, & Al Seadi, 2010) show that the eggs of common gastrointestinal worms and larvae of lungworm were inactivated after an eight-day retention time at a digestion temperature of at least 35 °C. Increasing the temperature to 53 °C inactivates them after less than 4 days. Many common viruses were shown to die under mesophilic conditions in the anaerobic digester – for example, bovine viral diarrhoea (5 minutes at 55°C or 3 hours at 35°C); Aujeszky's disease in pigs (10 minutes at 55°C or 5 hours at 35°C); and Johne's disease in cattle (caused by M. Paratuberculosis, which becomes inactive after 0.7 hours at 55°C or 6 days at 35°C).

Further studies show that if there are pathogenic bacteria in the feedstock, they will at the very least be reduced in number during the process. This was investigated for several stems of bacteria. The most likely reason is that the process bacteria are the best adapted to the feedstock and the other conditions inside the digester. The process bacteria that degrade sugars, fats and proteins are dominant in the digester and less well-adapted pathogenic bacteria do not survive the concurrency.

If very high amounts of pathogenic bacteria are fed into the process, however, they will be reduced but not entirely eliminated. Most types of biowaste and animal by-products (e.g. slaughterhouse waste, household waste, canteen leftovers etc.) need to be sanitised in order to eradicate animal pathogens or reduce them to an acceptable, sanitary level. This does not apply for manure, which can be spread directly on the fields, as long as digestate from manure is not included under EU fertiliser regulation.

There are a number of sanitisation techniques, including the following:

- Pasteurisation, which is done in a batch reactor. The material is heated up to above 70 °C for at least 1 hour. The particle size should not exceed 12 mm. Pasteurisation can be carried out upstream and restricted to the waste fraction that is at risk of containing pathogens. The heated material also helps to transfer heat to the subsequent digestion process. Another method is to pasteurise all digestate. Treating all digestate (rather than just the contaminated part) is more expensive, however, and requires more energy.
- Thermophilic digestion: if the feedstock is digested in a

thermophilic (> 50 °C) process and the hydraulic retention time (HRT) is above 14 days, then the digestate can be considered to be sanitised.

- Thermophilic composting: the material is sanitised in the same way as during thermophilic digestion, i.e., at >50 C and for longer than 14 days.
- Other validated methods - if the operator of a biogas plant can prove that other methods (like shifting the pH-value) ensure sanitisation, these methods can be accepted as well.

8.3 BENEFITS OF DIGESTATE AS ORGANIC FERTILIZER

For the plant operator and for the processors and users of digestate, its impact on soil microbes and aggregate stability is of high importance. In order to understand the different effects of digestate and untreated raw farm fertiliser on soil microbes etc., a closer look at the digestion process is necessary.
Besides degrading carbon and producing biogas, microbes in the digestion process also break down undesirable volatile organic compounds (such as iso-butonic acid, butonic acid, iso-valeric acid and valeric acid, along with at least 80 other compounds).If untreated, these compounds would cause an unpleasant odour when released into the atmosphere and would also have a negative impact on microorganisms in the soil. The following graphics show the degradation of organic compounds during the digestion process; GHG emissions by untreated and digested farm fertiliser; and the reduction of several types of volatile fatty acids during the digestion process.

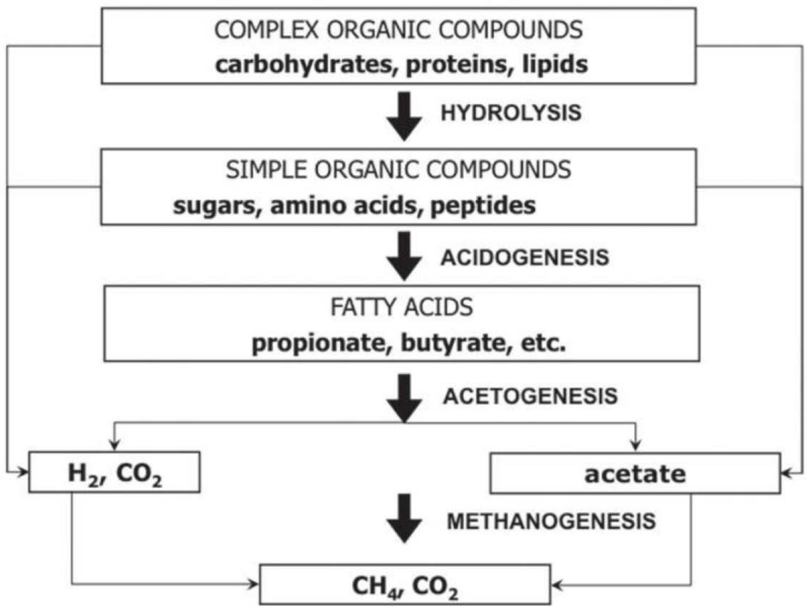


Figure 26: Degradation steps of organics within the anaerobic digestion process; © Drosg 2013.

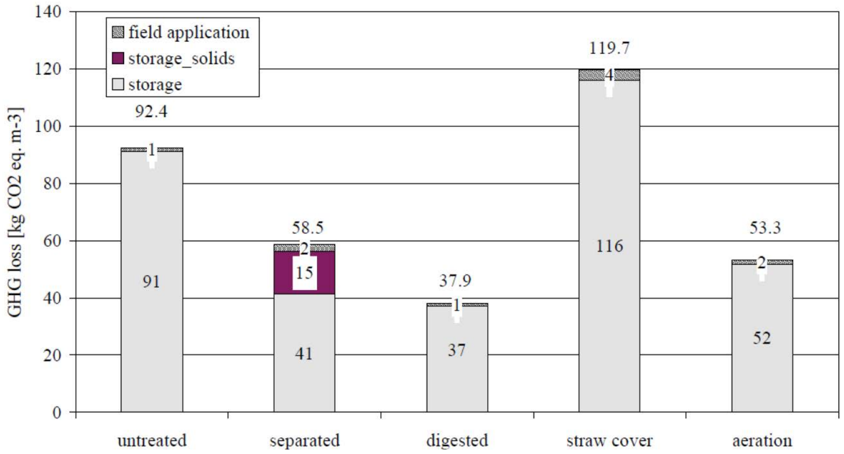


Figure 27: Greenhouse gas emissions during storage and after field application of dairy cattle; © Amon 2002.

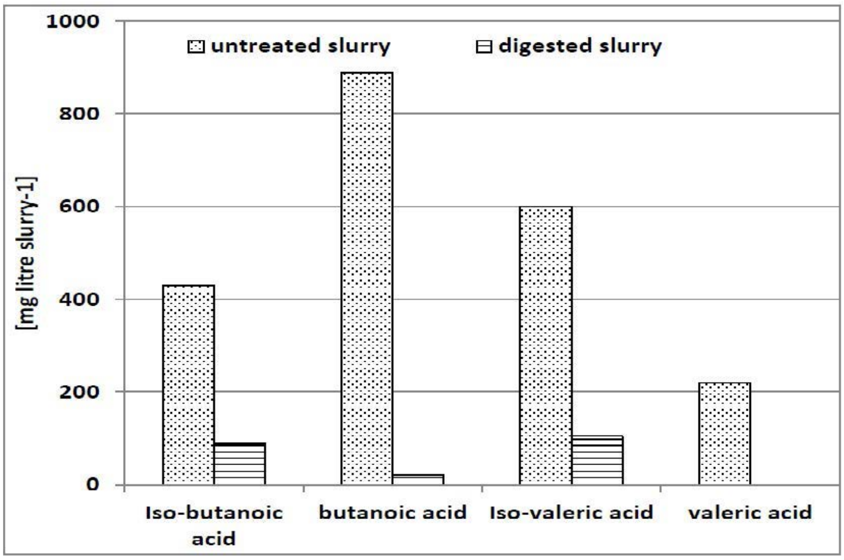


Figure 28: Concentration of different kinds of volatile fatty acids in raw farm fertilizer and digested farm fertilizer; © Hansen 2005.

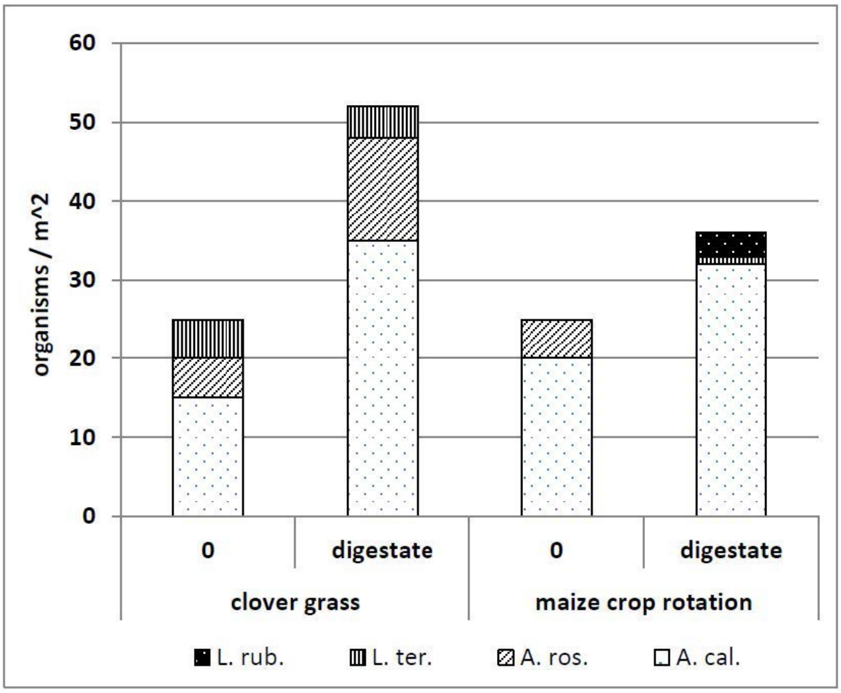


Figure 29: Presence of different kinds of worms in soil without application of digestate (=0) and with application of digestate to different crop rotations; © Hülsbergen 2016.

Due to the positive effect of digestate on microorganisms in the soil, we can also expect a positive impact on the aggregate stability of soil. This was investigated by Hülsbergen 2016 and is shown in Figure 30.

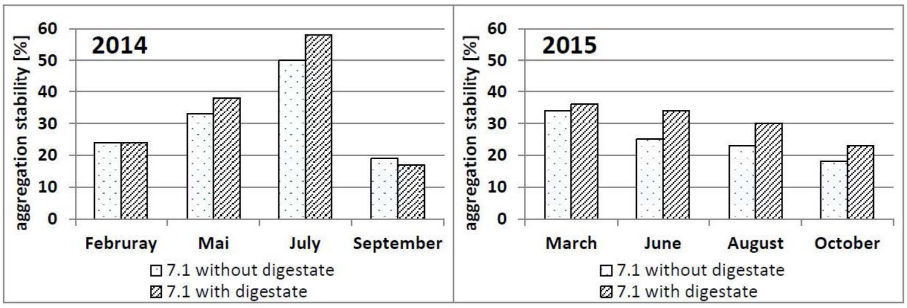


Figure 30: Comparison of aggregation stability of soil without application of digestate and soil aggregation stability with application of digestate; © Hülsbergen 2016.

Petz (2000) comes to the same conclusion. During his research, he discovered that the perennial application of digestate lead to a significant increase in the microorganism population in the soil, a higher aggregate stability and a significantly higher field capacity of around 13%. The improved aggregate stability is particularly important in terms of climate change and the associated changes to weather patterns (especially rain intensity and total annual rainfall). Another reason why digestate has a positive effect on soil is its humus-forming capacity. Reinhold showed in 2008 that digestate has a significant capacity to form humus (as set out in Figure 31). Nielsen et al. also compared the stability of carbon from different sources after application to silty sand (2018). After 500 days, carbon from bovine manure had the lowest mineralisation rate (15%) whereas carbon from different kinds of digestate mineralised between 25-47% (but was still behind bovine slurry, which had a mineralisation rate of around 50% and wheat straw, which had a mineralisation rate of nearly 70%). Digestate improved the aggregate stability of the soil significantly more than bovine slurry and slightly more than bovine manure.

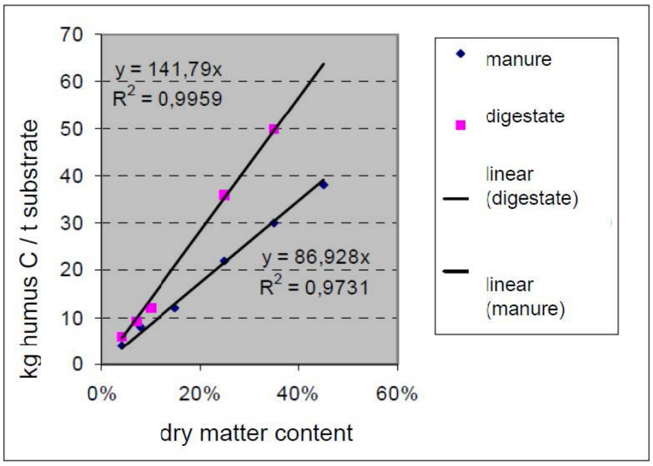


Figure 31: Comparison of humus forming possibilities of untreated manure and digestate; © Reinhold & Zorn, 2008.

Finally, two comparisons show the effect of digesting catch crops and straw. Based on research by Szerencsits in 2014, examining the yields of different kinds of catch crops and their organic matter losses during the winter season, Kirchmeyr (2016) made a comparison within BIOSURF between rotting the growth during the winter time, on the one hand and on the other, harvesting the growth from catch crops and using the digestate as organic fertiliser.

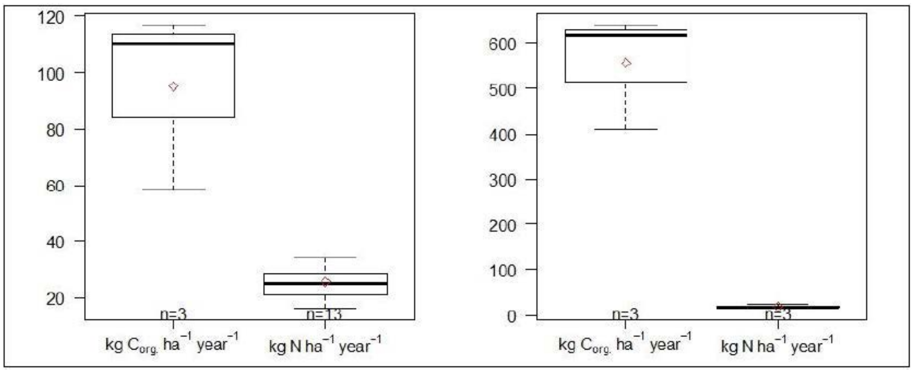


Figure 32: Rotting process of catch crops during winter periods: left: losses of Corg. and N per ha into ground water; right: losses of Corg. And N per ha into atmosphere; © Szerencsits 2014.

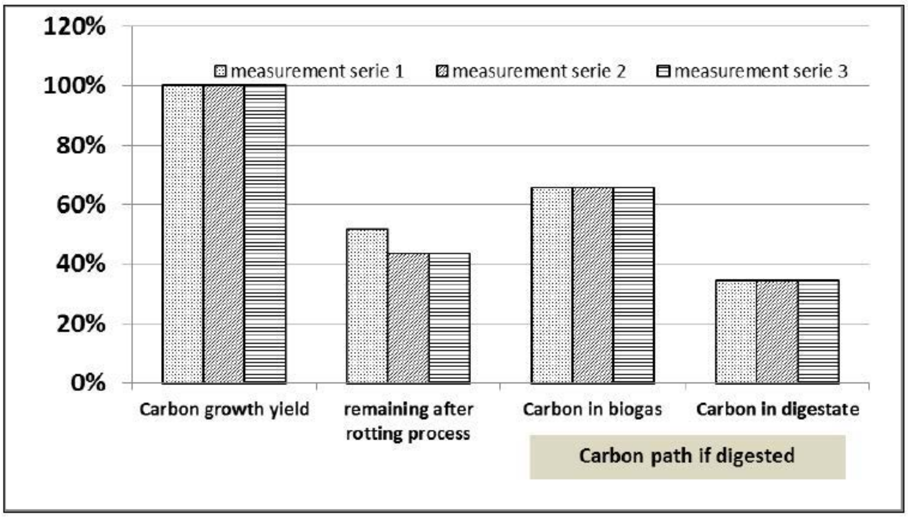


Figure 33: Comparison of Carbon path from catch crops: a) catch crops stay on the field to rot, b) growth of catch crops are harvested, digested and digestate is brought back to field; © Kirchmeyr 2016.

It is also important to note that N is fixed during the digestion process and therefore N losses can be minimised. All in all, high yield second crops may help significantly in avoiding wind and water erosion and raising soil fertility; when they are used to feed an anaerobic digestion process, additional energy can be produced and nutrient losses minimised.

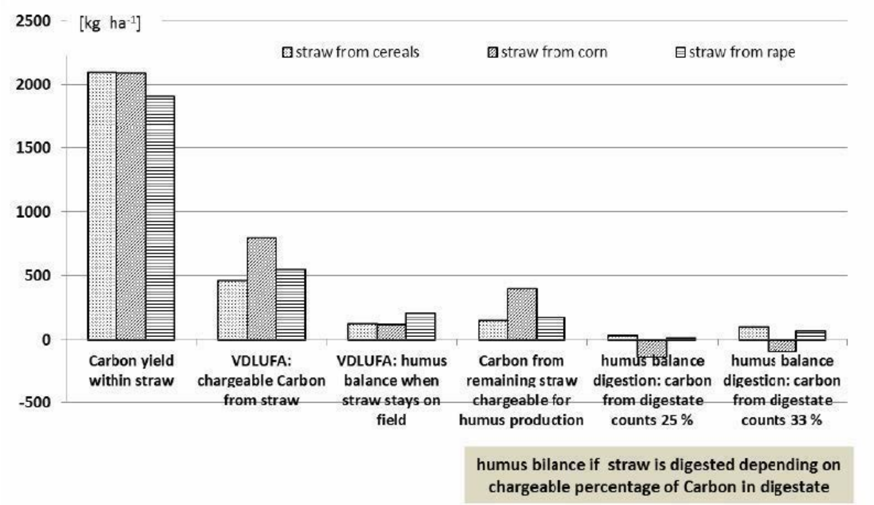


Figure 34: Humus forming ability of rotting process of straw compared to harvesting and digesting straw; © Kirchmeyr, 2016.

Depending on the calculation method for humus balance and especially on the factor for the humus-forming capacity of different kinds of carbon, harvesting and digesting certain amounts of grown straw may not have a negative impact on the humus balance compared to rotting the straw.

8.4 IMPURITIES

When digestate is used as fertiliser for plant nutrition, the aspect of possible impurities needs to be considered. When the feedstock used comes exclusively from clean sources – like energy crops, straw, farm fertiliser and by-products from the production of food, animal feed, beverages and renewable transport fuel – this aspect is less of an issue. When organic waste streams from households and catering or sewage sludge are digested, however, more attention must be paid to possible impurities. Plastic impurities, metal (especially heavy metals), glass, antibiotics, pharmaceutical residues and other chemicals are all problematic and their presence in digestate that is to be spread on fields should be completely or almost completely avoided. Within the EU, the special requirements in Annex II of the recently amended EU fertiliser regulation (2019/1009/EG) have to be satisfied.

EU fertilizer regulation Annex II: Restrictions on impurities (glass, metal, plastics)			
Size [mm]		amount [g kg_{DM}^{-1}]	
∑ of macroscopic impurities: (glass, metal or plastics)	> 2	5	In total
	> 2	3	For each separately
		2.5	For plastics: From 16.07.2026 on
		Reassessment before 16.07.2029	

Table 15: EU fertilizer regulation Annex II: upper limit values for impurities.

Every digestion plant treating organic waste that may include impurities uses an impurity removal device prior to the digestion process. In some cases, however, it may also be necessary to perform a second check in order to ensure compliance with the requirements contained in the EU fertiliser regulations. Another reason to include a second check is that no plant operator wants to spread undesirable impurities on agricultural fields. The additional step usually consists of sieving all of the digestate just before it flows into the storage tank. A number of studies of digestate have demonstrated the efficiency of this system.

When animal by-products are fed into the digester, a sanitation step is also required. This is usually done before the substrate is fed into the digester. The reason for this is efficiency: the feedstock is effectively pre-treated during the sanitation process, allowing for a faster break-down of organic material in the digester.

In special cases the sanitisation could also be carried out after the digestion process but the digestate should then be stored in a gastight storage tank which is connected to the gas system so that any remaining biogas can be collected.

8.4.1 SEPARATION, DRYING AND FURTHER UPGRADING

In smaller biogas plants, digestate is usually stored untreated. It can also be upgraded for several reasons:

- To produce recyclate which is needed to avoid an elevated dry matter content in the digester
- To produce a solid phase which can be sold to consumers
- To produce marketable fertilising products

Water content is most commonly extracted from digestate using a screw press.

Picture 51: Screw press to dewater digestate.

In warmer regions, sun-drying systems can also be used, in which the digestate is filled into a glass storage structure and turned by an automatically-driven turner. Ammonia and other gases, such as N_2O, may also be released during this process: These emissions should be limited because some gases, including N_2O, are potential Green House Gases. Ammonia losses should also be limited because they represent a loss of nitrogen which is an important fertiliser.

Picture 52: Left: decanter, right: automatically driven digestate turner.

Picture 53: Post-composting of digestate from a dry fermentation process; left: in a closed hall with automatic aeration through the compost windrow and collection and cleaning of exhaust air in a biofilter, right: windrow post-composting in an open hall.

Dryer belts are another frequently used practical solution; they allow the digestate to be dried using warm exhaust air from the CHP. The dried digestate can then be pelletised and sold for domestic gardening etc. Here, too, ammonia will to some extent be released as a gas, and must be removed from the exhaust air before its release into the atmosphere.

After a dry digestion process, on the other hand, what follows is usually a composting of the digestate. Several research projects have been conducted in recent years to examine the best ways of further upgrading digestate into a product which can directly replace mineral fertiliser. The relevant techniques include stripping, membrane filtering and osmosis, among others.

8.5 DIGESTATE STORAGE AND APPLICATION TECHNIQUES

As digestate is a valuable organic fertiliser, it should be applied in periods of plant growth. Depending on the climate conditions where the biogas plant is located, this might require that digestate is stored over longer periods when application would not bring benefits for plant growth or would even pollute the environment (for example, during the winter season).

In central Europe with its long winters, the required storage time can be anything from 6 to 9 months. Most storage tanks are built in-situ using concrete; precast concrete tanks or lagoons with double membranes (monitored for leakage) are alternative possibilities. Storage facilities can be open or airtight but airtight storage is increasingly a requirement because of the risk of emissions of methane and laughing gas from open storage tanks.

Covered storage tanks require an installed, fixed stirring system. Open storage systems can use these mechanisms as well but also have the option of using mobile stirring devices. Compared to the application of raw farm fertiliser, the use of digestate offers several positive effects, as mentioned above. Because the percentage of ammonia within the total nitrogen content is higher in digestate than in farm fertiliser, the application should be carried out with devices that reduce the release of ammonia into the atmosphere. Usually this is done with slurry tanks with additional trailing hoses or slurry cultivators. When digestate is applied to cereals or grassland during the growth season, slit injection is also an option. Additionally, loading from the storage tank into transport tanks and from the transport tanks into the field application device should be carried out via a sealed connection.

Picture 54: Glasshouse with vegetables grown on effluent from digestate screw press.

Picture 55: Digestate storage tank: top left: open storage tank, top right: airtight gas storage tank with a double membrane layer and connection to the gas system, below: open lagoon with double layer membrane to monitor tightness.

Picture 56: For the transport over longer distances trailers are used often.

Picture 57: Top: filling station for slurry tanks and slurry tank with trailing hoses; Bottom: slurry spreader without tank and slurry tank with slurry injection.

9 BIOGAS STORAGE

Thanks to the scientific and technical advances that have taken place during recent decades, professionally-operated biogas plants often run very consistently at full load capacity. This is most often the case in set-ups where feedstock can be stored or delivered at frequent, regular intervals and therefore can be fed into the digestion process exactly when needed. Biogas plants operating in this way can reach full-load-hours above 8,000 h a^{-1}. When organic residues from households and caterers or other seasonally-accruing feedstocks are the main substrates, biogas production will vary according to feedstock delivery. This is because the amount of organic waste from households differs between seasons and carbon-rich effluent from sugar plants or biofuel plants also occurs only seasonally etc. Furthermore, biogas usage may also fluctuate according to consumer demand and can be interrupted for maintenance reasons etc. When the gas-consuming facility is not in operation, e.g. during maintenance, the biogas produced must be stored. This occasional imbalance between biogas production and biogas use is generally compensated for by the use of special gas storage systems.

The size of gas storage systems varies significantly. Plants where the use of the biogas produced is immediate and unrestricted usually have a biogas storage capacity of 3-10 times the hourly biogas production[2].

As biogas is a very reliable and flexible energy source, attention has also turned to the to the use of biogas to supplement supply to the electricity grid. Biogas could, for example, help to balance the electricity grid by producing peak load electricity or control energy or by being applied over a specific time period. Although some research has been done to examine ways of varying biogas production inside the digester according to consumer demand, the results show that it is better to run the digester constantly and to store the biogas in the periods where the electricity is not required. Biogas plants used for electricity in this way usually have biogas storage systems that can store the biogas produced for one day or even longer. An important consequence is that the CHP then often has double or even 3 times the electric capacity it would have if operated continuously. In Germany, for example, there are several thousand biogas plants capable of flexible operation, in which the CHP can be turned on (to produce electricity) or off (requiring biogas to be stored). This allows electricity generation to match power consumption more closely, even when demand fluctuates by several GW_{el}.

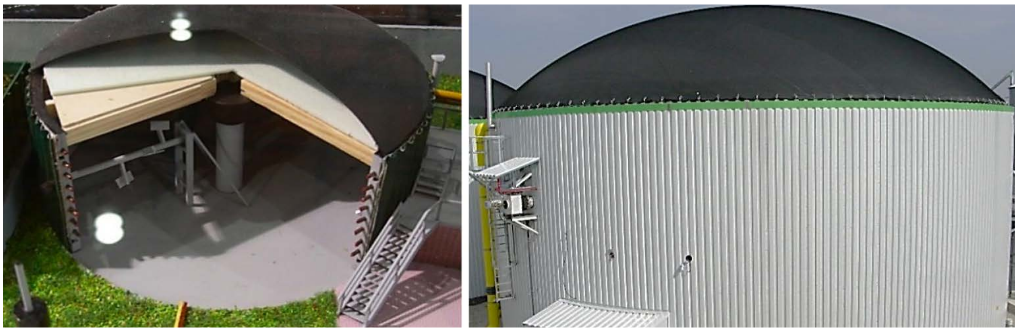
The most common biogas storage devices are different kinds of membranes (EPDM, PVC, etc.). Almost all of them are low-pressure systems running with just a few millibar over-pressure (depending on the manufacturer and the system, up to 50 mbar). These types of gas storage can be categorised as follows:

> Low pressure systems (membranes)
  - Single membrane
    - As roof of the digester
      - Self-supporting through biogas pressure (with or without outer net to control the maximum size)
      - Suspended from a middle pile
    - Incorporated in the roof of the digester and suspended
    - Separate in-house systems
  - Double membrane
    - As the roof of the digester
      - Inner membrane as gas membrane
      - Outer membrane as weatherproof cape
        - Suspended from a middle pile
        - Shaped with air from an external blower
    - Stand-alone systems
      - Inner membrane as gas membrane
      - Outer membrane as weatherproof cape (shaped with air from an external blower)

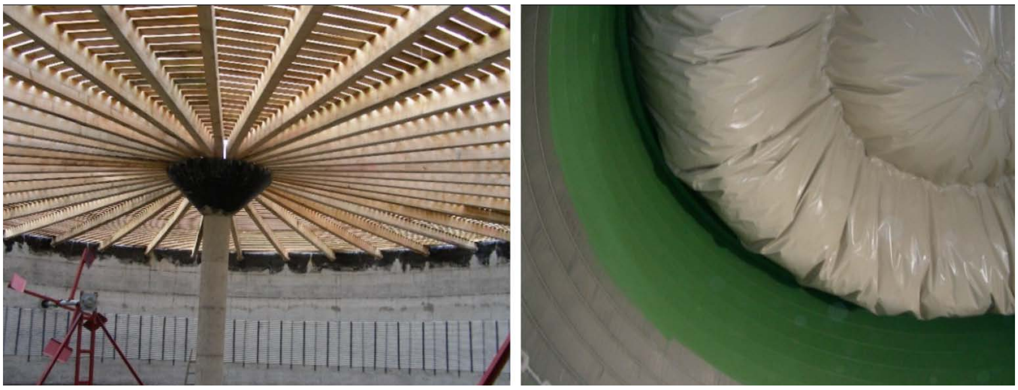
There are many different kinds of biogas membrane storage system on the market. Each manufacturer has their particular design. In contrast to steel or gastight concrete systems, membrane storage systems are not completely gastight. The associated technical guidelines therefore include requirements for permeability, tearing strength, weather resistance and durability (especially with regard to ultraviolet radiation and aging), in order to limit gas emissions and avoid leakage.

Property	Requirement
Tearing strength	Min. 3 000 N $5cm^{-1}$ (if a membrane cannot fulfill this requirement itself it must be shaped by a net)
Permeability	Max. 1 000 ml m^{-2} $d^{-1}bar^{-1}$
Ultraviolet radiation stability	Declaration from the manufacturer on secure holding period

Table 16: Technical requirements for biogas storage membranes; © BMWFW, 2017.



Picture 58: left: cross section of a model with single membrane; right: digester with single EPDM membrane.



Picture 59: A view from the inside of a digester to the top, left: wooden roof under the gas membrane; right: gas membrane from the inside.

Picture 60: Single membrane gas storage in external housing.

Picture 61: Left: double membrane with middle pole, right: digester with inner single membrane suspended from roof on the left and digester with double membrane shaped by air blower on the right.

In double membrane storage systems in particular, where the outer membrane is shaped by an air blower, the height of the outer membrane can be varied according to consumer needs. Resistance to wind, snow and other weather is achieved by correctly maintaining and adjusting the pressure of the air blower.

Picture 62: Stand-alone double membrane biogas storage systems shaped with air blower.

Every gas storage system also includes a number of safety devices in order to avoid over-pressure and protect against lightning damage, damage caused by vehicles and other hazards. These devices are described in the chapter on MCR.

A storage system that was commonly used in the past and remains to some extent a popular option today – especially for the storage of gas in European cities – is the wet gasometer. It consists of a large, cylindrical container filled with water, in which another cylindrical container is placed upside down. The gas is brought in through a pipe, which enters the storage from the bottom of the water-filled container and delivers the gas just above the water level. The pressure is maintained by the upper container, which rises as gas is filled in and lowers as gas is drawn off.

Picture 63: Wet gasometer directly included in the digestate storage tank.

- High pressure systems (steel tanks)

Although biogas is usually stored in low pressure systems, high-pressure systems are also available. These systems are usually installed when higher pressure is needed in the subsequent application – for use as transport fuel, for example, where pressure in excess of 200 bars is required. In most cases, these storage tanks are made from steel. It is necessary to dehumidify and desulphurise biogas going in to steel storage systems, as otherwise it would cause corrosion. Typically, the biogas is upgraded to biomethane quality, so that highly concentrated biomethane (without CO_2) can be filled into the gas cylinder.

Picture 64: High pressure biogas storage systems with piston compressor.

The use of former natural gas storage caverns as seasonal storage systems for biogas is currently not widespread. In the future, these seasonal storage facilities, which could be used after biogas has been upgraded to biomethane and after the gas has been injected into the grid, will become more important within the EU.

10 BIOGAS APPLICATIONS

Biogas is a very versatile renewable energy source, which brings with it several advantages and can be used in a number of ways. Possible applications are:

> Raw biogas (with minor purification)
  - Heating & cooking
  - CHP: combined heat & power production
  - Gen-set, a gas engine coupled with a generator for electricity production
  - Transport fuel

> Biogas upgraded to biomethane
  - Gas grid injection
  - Transport fuel
  - CHP: combined heat & power production
  - Heating & cooking
  - Raw material for the chemical industry

The most common use of biogas within Europe is electricity production via CHP; the associated heat production is generally used on site or for district heating. Increasing amounts of biogas are being upgraded to biomethane, however, and the level of gas grid injection of biomethane is increasing fast.

When biogas is produced, it is initially at the same temperature as the digester content and is saturated with water vapor. As it starts to cool, for example in the gas pipelines, water vapor starts to condense, but the biogas is still saturated with water vapor. Both characteristics can cause malfunction or even damage – for example if condensed water blocks the piston. It is therefore important to remove condensed water at the lowest point in the gas pipes, to avoid water flowing into the CHP (or other devices where it could cause damage). It is also necessary to reheat the biogas before critical applications so that the biogas is no longer saturated with water vapor (which could start to condense and damage the CHP).

The most valuable biogas component for further application is methane, and to lesser extent hydrogen. Hydrogen sulphide and ammonia would also offer energy yield but can cause unwanted emissions or even damage to equipment. Biogas therefore usually has an energy content between 5 and 7 kWh_{Hi} per m³, mainly determined by the methane content. The main components of biogas are shown in table 17.

Component		Energy content [kWh_{Hs} Nm^{-3}]	[kWh_{Hi} Nm^{-3}]	[kWh_{Hi} kg^{-1}]	Density [kg m^{-3}]	Share within biogas [$\%_{vol.}$]
Methane	[CH_4]	11.06	9.97	13.85	0.72	50 – 70
Carbon dioxide	[CO_2]				1.977	30 - 50
Nitrogen	[N_2]				1.25	0 - 5
Hydrogen Sulfide	[H_2S]	7.03	6.48	4.22	1.536	0 - 2
Hydrogen	[H_2]	3.54	2.99	33.28	0.09	0 - 1
Oxygen	[O_2]				1.429	0 - 1
Ammonia	[NH_3]	4.82	3.99	5.17	0.771	0 - 2

Table 17: Biogas: components and their properties (Nm-3: 0°C 1013 mbar); © ÖNORM S2207, ÖVGW GB 220.

10.1 GHG MITIGATION POTENTIAL

Biogas is a valuable renewable energy source with enormous potential to mitigate greenhouse gas (GHG) emissions by digesting different kinds of organic material.
In order to combat climate change, GHG emissions need to be reduced drastically, as set out in in the Paris Agreement. Achieving this goal requires tremendous effort from all sectors that emit greenhouse gases. In agriculture, the storage of manure from animal husbandry is a leading source of GHG emissions but it also has the capacity to be a major source of renewable energy via anaerobic digestion, as the following graphics show.
The GHG mitigation potential of AD stems from many aspects of the production process, of which a few are outlined below.

10.1.1 TREATMENT OF FARM FERTILIZER

Figures 35-37 give an overview of average daily excrement production of different farm animal categories in specific European countries, followed by the associated GHG emissions and possible energy yield of the different manures via anaerobic digestion. All data are derived from National Inventory Reports from the countries in question. The amount of excrement produced by animal husbandry varies enormously according to animal species, diet, climate conditions and animal performance.

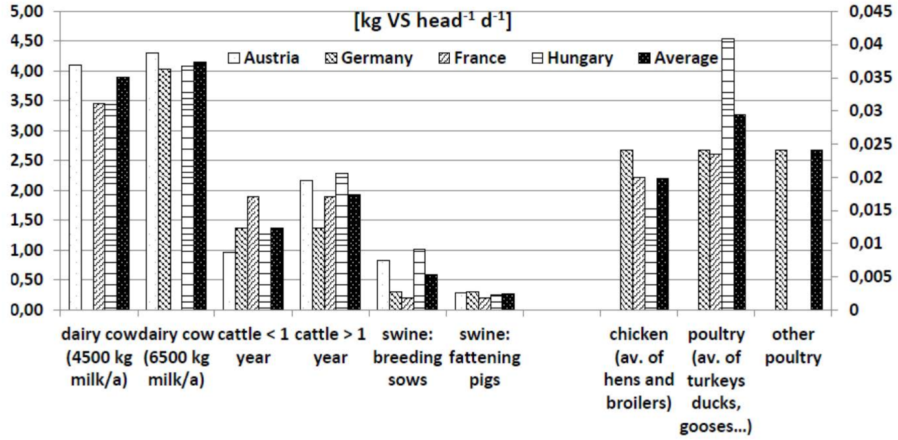


Figure 35: VSi (average daily volatile solids) excreted (kg) from animal species - per country and animal category [kg VS head-1 d-1]; © Kirchmeyr 2016.

Based on average daily excretion of volatile solids, climate conditions, husbandry and manure management, the average level of CH_4 and N_2O emissions can be calculated. The methodology used in making the calculation is based on the method set out in the IPPC report (IPCC - Ch 4, 2000).

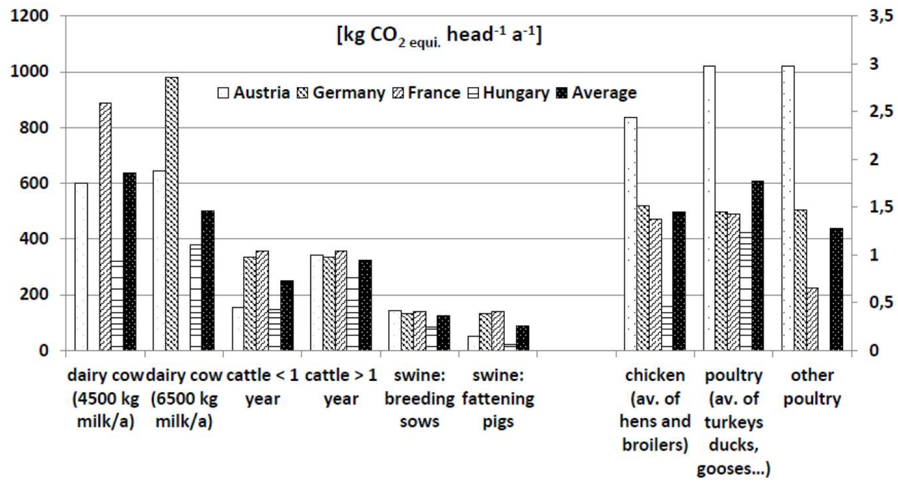


Figure 36: CO_2 equivalent emissions from slurry tanks per animal and year (considered:CH_4 and N_2O) expressed in kg CO_{2equi}. per head and year; © Kirchmeyr 2016.

Instead of storing farm fertiliser untreated in slurry tanks, it can be digested in biogas plants and used to produce renewable energy. Figure 38 gives an overview of possible energy yield from different manures based on the amount of volatile solids they contain (as set out in Figure 36).

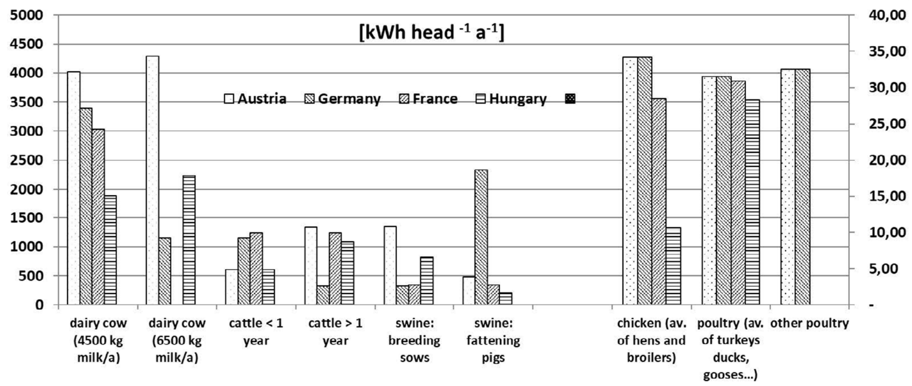


Figure 37: Possible energy yield from excrements of husbandry via anaerobic digestion expressed in kWh head-1 a-1; © Kirchmeyr 2016.

Untreated, stored manure causes GHG emissions, whereas the digestion of the same manure produces renewable energy, meaning that the digestion of manure can even represent negative emissions compared to fossil fuel.

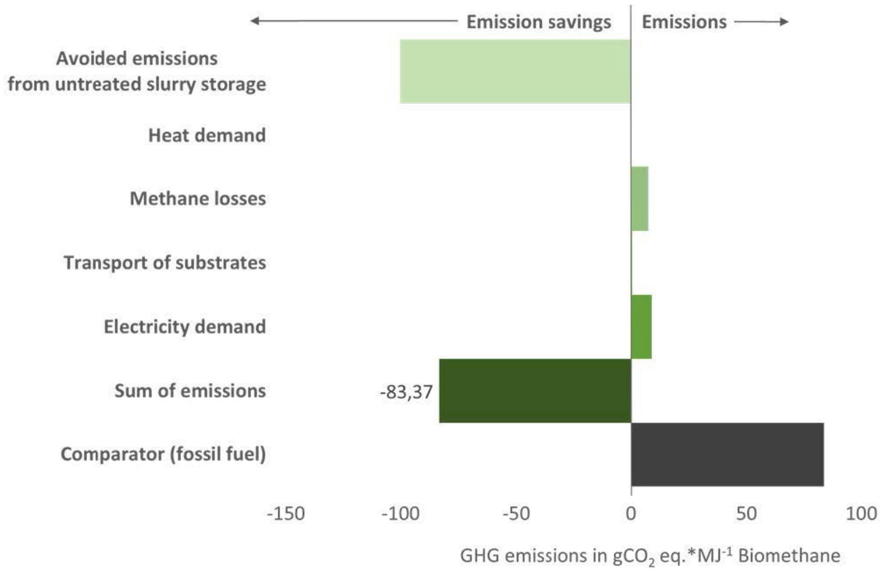


Figure 38: Sum of emissions of biomethane production from farm fertilizer compared to fossil fuel comparator of RED II expressed in g CO_{2eui} MJ^{-1}; © Mayer S. et al. 2016.

10.1.2 TREATMENT OF STRAW AND OTHER AGRICULTURAL RESIDUES

As already shown in the chapter about digestate storage and use, the treatment of straw and second crops offers benefits to agriculture without negative effects on humus and the microorganism content of the soil. Compared to fossil fuel, straw and agricultural residues also offer a very significant reduction in greenhouse gas emissions.

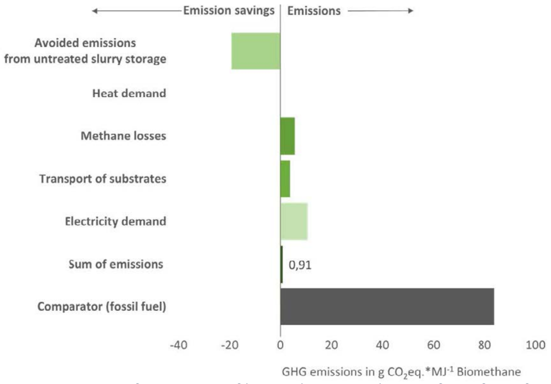


Figure 39: Sum of emissions of biomethane production from farm fertilizer and straw compared to fossil fuel comparator of RED II expressed in g CO_{2eui} MJ^{-1}; © Mayer S. et al. 2016.

10.1.3 TREATMENT OF ORGANIC WASTE

Manure and straw are typical agricultural substrates that usually stay within the agricultural cycle, whether processed via anaerobic digestion or not. The anaerobic digestion of domestic biowaste, however, provides an opportunity to recover nutrients that would otherwise be lost, as well as replacing mineral fertiliser. Figure 40 gives an overview of the average energy demand and GHG emissions of macro-nutrient mineral fertiliser production. Table 18 shows the average macro-nutrient content in biowaste collected as organic waste from domestic households.

Average main nutrient content of bio waste		
[kg N t_{FM}^{-1}]	[kg P_2O_5 t_{FM}^{-1}]	[kg K_2O t_{FM}^{-1}]
6.9	1.95	5.5

Table 18: Main nutrient content of bio waste; © Kirchmeyr 2016.

Although nutrient recovery and especially phosphorus recycling will be a very important issue in the future, the most important driver currently for digesting organic waste streams is the avoidance of the emissions that are generated by landfilling organic waste. Figure 41 shows the emissions avoided when organic waste is not landfilled, the emission credits for renewable energy production and the emission credits for recycling nutrients. Even if the landfilling of organic waste is banned and landfill emissions consequently no longer need to be taken into consideration, the GHG mitigation of digesting biowaste would be 80% relative to fossil fuel (RED II).

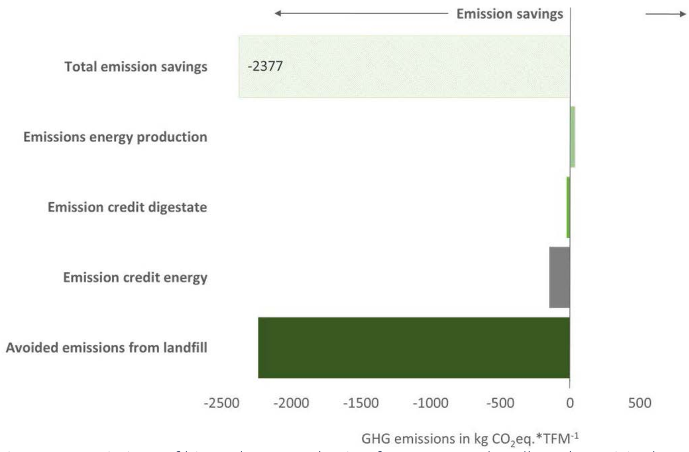


Figure 40: Emissions of biomethane production from separately collected municipal organic waste expressed in CO_{2equi} t_{FM}^{-1}; © Mayer 2016.

10.2 APPLICATION VIA COMBINED HEAT & POWER (CHP)

To date, biogas in Europe has most commonly been used to produce electricity & heat in combined heat & power facilities (CHP) on site at the biogas plant. Electricity from biogas can be produced in micro gas turbines, Stirling engines, internal combustion engines or within fuel cells. Each technique comes with its own particular requirements for the biogas being used. To avoid damage to the equipment it is therefore necessary to check the manufacturers handbook. As CHP units are the most common way of producing electricity from biogas, the following explanations focus on this technology.

To avoid damage to the internal combustion engine, biogas used in CHP needs to be purified. Aside from water vapour, the possible impurities and their amounts depend principally on the feedstock used. Some of the most likely impurities are :

- Hydrogen sulphide
- Water
- Siloxane

Sulphur is an essential nutrient for all living species; it is transported into the biogas plant in the feedstock and is partly converted to H_2S in the digester. Sulphur molecules such as H_2S cause corrosion and every engine manufacturer prescribes an upper limit for hydrogen sulphide. The concentration of hydrogen sulphide in raw biogas depends very much on the sulphur content of the feedstock. Typical concentrations can range from below 100 up to several thousand ppm. H_2S can be reduced by a number of desulphurisation techniques, including biological conversion, or chemical or physical treatment of raw biogas. The choice of technology depends on the biogas plant's design and on the feedstock used. If feedstock with a relatively low sulphur content is used, biological treatment within the gas space of the digester is a very cost-effective technique and therefore often used. During this treatment, the bacteria Sulfobacter oxydans converts hydrogen sulphide in the presence of oxygen to elementary sulphur. The equipment set-up is simple: all that is needed is a blower that blows some air into the top of the digester. The bacteria's only further requirements are other life-essential nutrients (provided inside the digester) and a place to establish themselves. Some digesters are constructed in such a way as to offer enough surface for these bacteria to settle.
This process can also be carried out in external desulphurisation devices – airtight towers containing areas where bacteria can get established, fed by a nutrient solution which is spread from above, washing down any elementary sulphur that is produced.

Biogas is blown through this type of desulphurisation tower from the bottom up. Chemical desulphurisation is carried out in a different kind of installation. It is mostly done by adding iron compounds (iron III chloride, iron II chloride, etc.). Iron compounds fed into the liquid digester content will bind to the sulphur in the digestion liquid. Chemically bonded sulphur cannot be released into the biogas. The third commonly used method is adsorption on activated carbon. This method is typically used (often in combination with other methods) if the biogas is to be upgraded to biomethane and needs to comply with very low and strict maximum values for H_2S. The hydrogen sulphide is adsorbed on specially conditioned activated coal.

Because biogas is saturated with water vapour, it starts to condense the moment the biogas temperature is lowered, e.g. in the pipes behind the digester. To avoid water entering the engine, most plants cool the biogas in underground pipes or via a water cooler. The condensate must be collected at the lowest point of the pipes and discharged in a condensate trap. As the biogas is still saturated with water vapor after cooling, it is important to heat the biogas up again so that the relative humidity drops below 100%. This is usually done with exhaust heat from the blower and with a back-up electric heating system.

Siloxane only occurs if biogas is produced from sewage sludge or special foam-inhibiting agents are applied in the digester. Siloxane could cause deposits on the spark plug, the injection valves, the exhaust valves and on the surface of the piston, leading to damage to the engine. Most plants using sewage sludge install a safety step in the form of an activated coal filter so that possible siloxane can be removed if it occurs.

Picture 65: Left: blower for desulhuration with air, middle: elementary sulphur within a gas pipe, right: sulphur at the top of the digester.

Picture 66: Left: external desulphurization column, middle: padding material for sulfobacter oxydans within external desulphurization column, right: activated coal filter.

Picture 67: External biogas coolers with integrated particle separator.

According to the Paris Agreement, energy production must be switched completely to renewable energy sources in order to combat climate change.

Electricity production from biogas offers many advantages: it is very reliable, storable, can be applied flexibly and offers the most full load hours of all renewable electricity production techniques. A forecast scenario of future electricity production shows very volatile production from non-biomass-driven renewable electricity sources. With biogas, production can be adjusted to meet demand, making it possible to provide peak load production and even control energy production so that the electricity grid is stable and supply is secure.

		Best 25 %	Average of all plants	worst 25 %
Full load hours	[h a^{-1}]	7 374	7 350	6 174

Table 19: Full load hours of Austrian Biogas plants in 2018; n= 177; © BMNT 2018.

Table 19 shows typical full load hours of biogas plants. In contrast, solar and wind power fluctuate. If, in the future, electricity comes primarily from fluctuating renewable sources, security of supply will become a major issue. Energy systems must provide electricity even when the sun is not shining and the wind is not blowing. Biogas can be stored when there is enough electricity from wind and sun and used when solar and wind supply fall short.

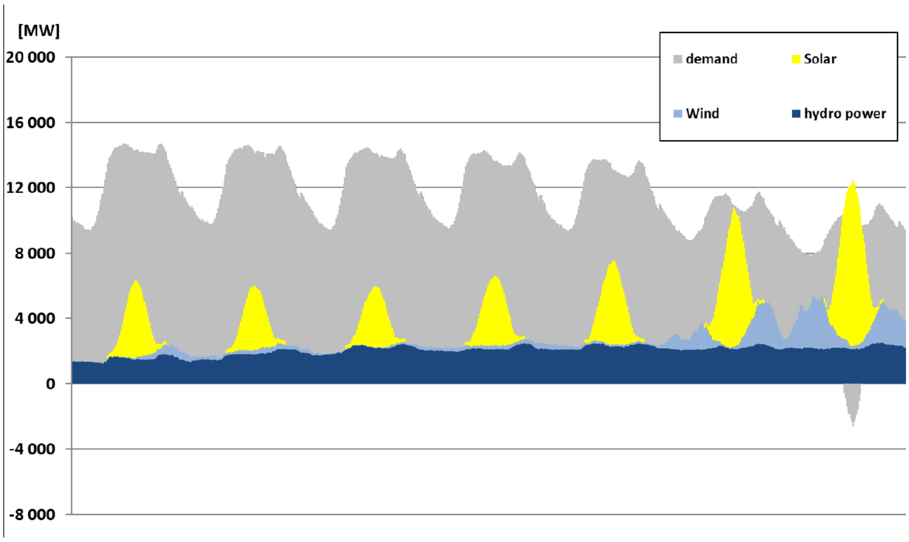


Figure 41: Forecast of Austrian electricity demand and supply from volatile renewables in week 6 of 2030; © Stürmer 2018.

It is also common practice to use CHPs for off-grid electricity production. Here, biogas can also be a good renewable source. Just as in the production of electricity for the grid, electricity produced for off-grid consumption is likely to be needed all the time, even when the sun and wind do not provide enough energy. In practice, a diesel engine is often installed as a back-up. Biogas makes it possible to fuel the generating engine with locally available resources. Additionally, a CHP driven by biogas can deliver electricity reliably, which is an important consideration in the many areas around the world where electricity supply is unstable or intermittent. There are biogas installations that were constructed first and foremost to avoid blackouts in the electricity grid.

The electrical efficiency of a CHP unit depends on its size. In general, CHP efficiency has improved over the last two decades: the electric efficiency of a mid-size CHP is currently around 40%; larger units can reach an electric efficiency of over 43% for the whole unit. Some CHP engines can be driven by biogas alone, with a spark for ignition. In other set-ups, dual fuel engines are used, where the injected biogas is ignited by a liquid fuel which is usually around 5% of the total energy demand. The ignition fuel can be diesel or biofuel, but restrictions on using fossil fuel as ignition fuel mean that a biofuel is more commonly used. The most widely used engines are single fuel engines that operate as gas Otto engines. To produce electricity, the gas engine is coupled with a synchronous or asynchronous generator. Synchronous generators have the advantage of being able to produce electricity without an impulse from the electricity grid. Asynchronous generators are only used in CHP plants below 100 kW_{el}. As the temperature of the surrounding air has an important influence on the electric efficiency, it is important to steer the cooling air directly to the generator and then to the engine.

A gas engine requires cooling; most frequently, this is achieved via a water-cooling system. During cooling, the cooling water is typically warmed up to about 90-95°C. This heat can be used not only to heat the digester also for many other purposes, such as heating houses, drying crops or wood, in greenhouses or in industrial processes requiring heat. In addition to the heat from the cooling cycle, the heat from the exhaust can be captured via an external heat exchanger.

The total efficiency of the biogas plant, and especially of the gas engine, is highly dependent on the use of the heat because the electric efficiency is around 40% and the thermal efficiency is often higher than that. More energy is converted to heat than to electricity. An efficient biogas plant should always be equipped to use the thermal energy peoduced.

It is important to follow the manufacturer's instructions concerning the minimum temperature of exhaust gas after the heat exchanger, in order to avoid corrosion and sediment and associated damage to the heat exchanger. New CHP installations run close to 90% total efficiency (electricity plus thermal energy). With a special heat exchanger, steam production is also possible. Corrosion of the CHP due to impurities in the biogas is one risk to be avoided; the coolant liquid is a further possible cause of corrosion, which needs to be considered. The use of untreated fresh water is not allowed by most CHP manufacturers; the water must be desalinated and treated with additives.

To avoid unwanted emissions, CHPs must be checked regularly and must comply with strict emission limits. CHPs have their own measurement, control and regulation (MCR) systems in order to achieve a high level of performance and comply with the maximum values for emissions.

Pollutant	[mg Nm^{-3}]
Sulphur dioxide [SO_2]	40
Nitrogen oxide [NO_x]	190
Dust	-

Table 20: Upper limit values for new CHPs above 1 MWth input using renewable gases referred to 273.15 °K, 101.3 kPa and standardized oxygen content in the off gas of 15 % ; © 2015/2193/EU.

Pollutant	[mg Nm^{-3}]	
	< 250 $kW_{th.}$	250 – 1 000 $kW_{th.}$
Sulphur dioxide [SO_2]	-	310
Nitrogen oxide [NO_x]	1,000	500
Carbon monoxide [CO]	1,000	650
Formaldehyde [HCHO]	60	60
Dust	-	-
For bigger combustion plants EU directive 2015/2193 is applicable.		

Table 21: Upper limit values for new CHP´s using biogas referred to 273.15 °K, 101.3 kPa and standardized oxygen content in the off gas of 5 % ; © Technische Grundlage für die Errichtung von Biogasanlagen. BMWFW 2017.

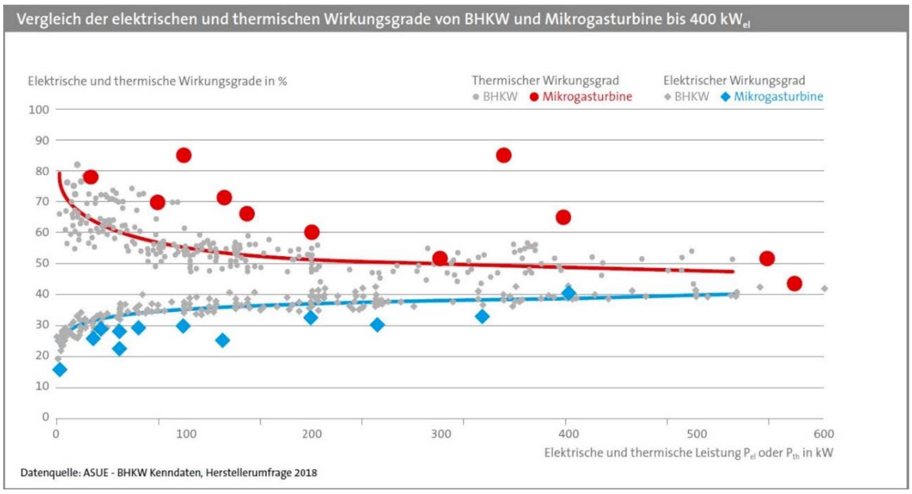


Figure 42: Comparison of total, electric and thermal efficiency of CHP and micro gas turbines depending on installed electrical capacity; © ASUE 2018.

The efficiency of a CHP unit depends very much on its size. The bigger the size, the higher the electrical efficiency but the lower the thermal efficiency. The grey dots in Figure 43 show results from the measurement of gas engines. The red line shows the average thermal efficiency; the blue line shows the average electric efficiency. Both the red and the blue dots represent measurements taken from microturbines.

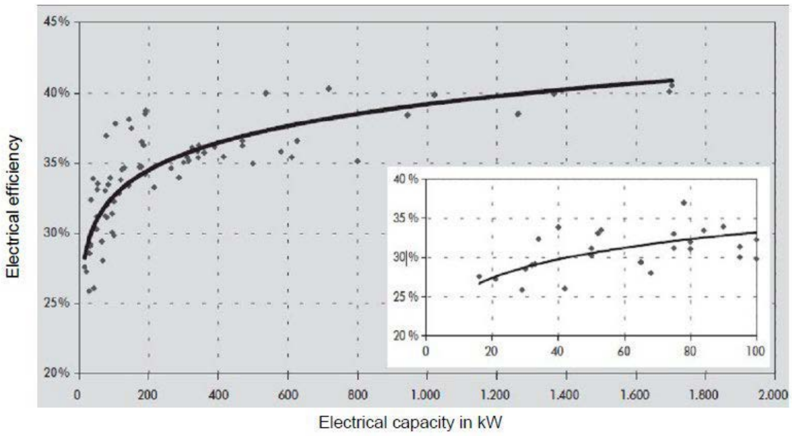


Figure 43: Electric efficiency of various CHP´s; © Biogas guide book 2019.

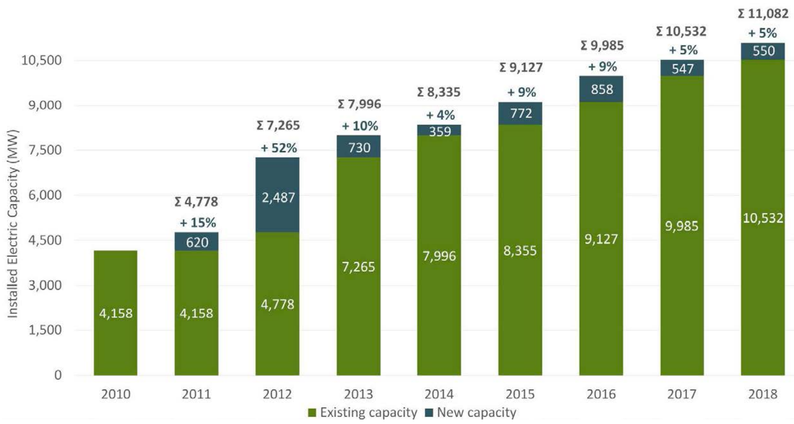


Figure 44: Development of installed electric capacity of biogas plants in Europe expressed in MWel.; © EBA 2020.

Picture 68: CHP unit: left: steered intake air, steering, generator, heat exchanger and gas engine, right: fully equiped CHP container with cooling, flare, heat exchanger and exhaust pipe above the container.

10.3 BOILERS AND COOKING

In some cases, biogas can be used directly to produce heat. In Europe, this is not done very often because electricity has a much higher value and can be used more flexibly than heat.

Where it is done, however, it is mainly to produce process heat in industry, to generate steam, or to provide peak load and failure reserve heat for district heating systems. If a district heating system is powered by a biogas plant, the base load for the heat supply comes primarily from the CHP unit of the biogas plant.

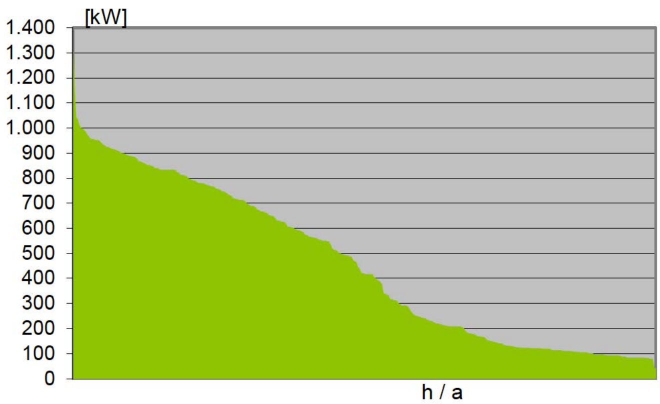
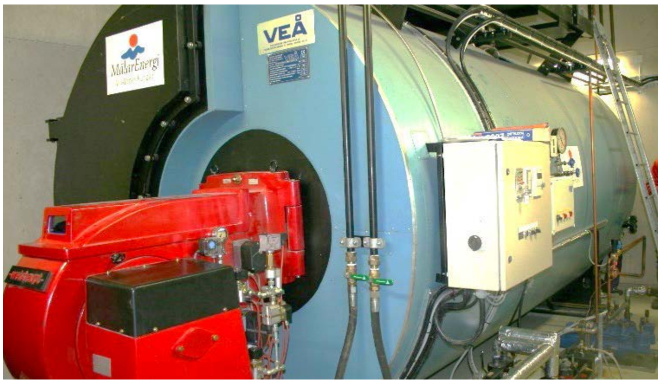


Figure 45: Typical heat demand curve in a local district heating system © AKBOE 2012.

Figure 45 shows that heat demand varies greatly throughout the year. Peak loads (the left-hand side of the graph) are only needed for a few hours per year, while the base load is almost always needed.



Picture 69: Typical peak load boiler for biogas with a capacity of 7.2 MW_{th}.

10.4 UPGRADING BIOGAS TO BIOMETHANE

Biogas consists of methane, carbon dioxide and some other, minor components. If the biogas is cleaned, the minor components eliminated, and the methane separated from the carbon dioxide, almost pure biomethane can be achieved. Methane is the main component of natural gas, which typically contains 90 to 97% methane.

Upgrading units can purify biogas up to 90-99% methane content, meeting the requirements of natural gas. This offers a further wide range of applications, including:

> Direct use as transport fuel
> Gas grid injection and subsequent use in
  • Transport
  • Heating & cooking
  • Combined heat & power

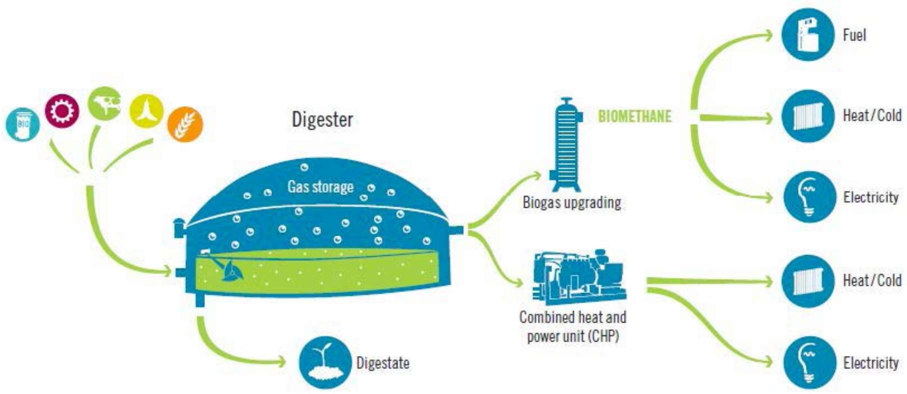


Figure 46: Process of biogas production and its possible applications; © Fachverband Biogas 2017.

In Europe, two main grids are available for the transportation of energy – the electricity grid and the gas grid. Both grids play a key role in delivering energy to consumers and in ensuring security of supply, and each has its own specifications. The characteristics of the two grids are explained here using data from Austria. In 2018, demand for energy delivered through the gas grid reached 90.7 TWh, compared to 66.4 TWh for the electricity grid. While the electricity grid reaches a peak load of around 11 GW_{el}., the gas grid exceeds this value nearly threefold, reaching a peak load of around 28 GW_{th}. Due to its topographic conditions, the electricity grid in Austria can make use of a very high amount of installed hydro pump storage, with a total storage capacity of 3.3 TWh_{el}. and a maximum performance of 6.4 GW_{el}. The Austrian gas system, however, has a cavern storage capacity of 91.8 TWh_{th}. in total and a maximum performance of 44.6 GW_{th} (E Control 2019). It is not only the larger maximum storage capacity of the gas system that is significant but also the maximum possible performance at times when demand is very high and the actual stored energy is at its lowest point. These instances usually occur in the first two months of the year, when low temperatures cause high energy demand, hydro power from rivers reduces and wind and PV can be at the lowest level. Figure 47: Maximum available capacity of pump hydro storage compared to gas storage within caverns per week; © ENTSO E, E-Control shows these points of high demand and critical supply for both grids. While pump hydro storage can provide security of supply for about 3 days, gas storage systems can secure supply for more than 20 days. These graphics bring new facts to light and underline the importance of the gas grid.

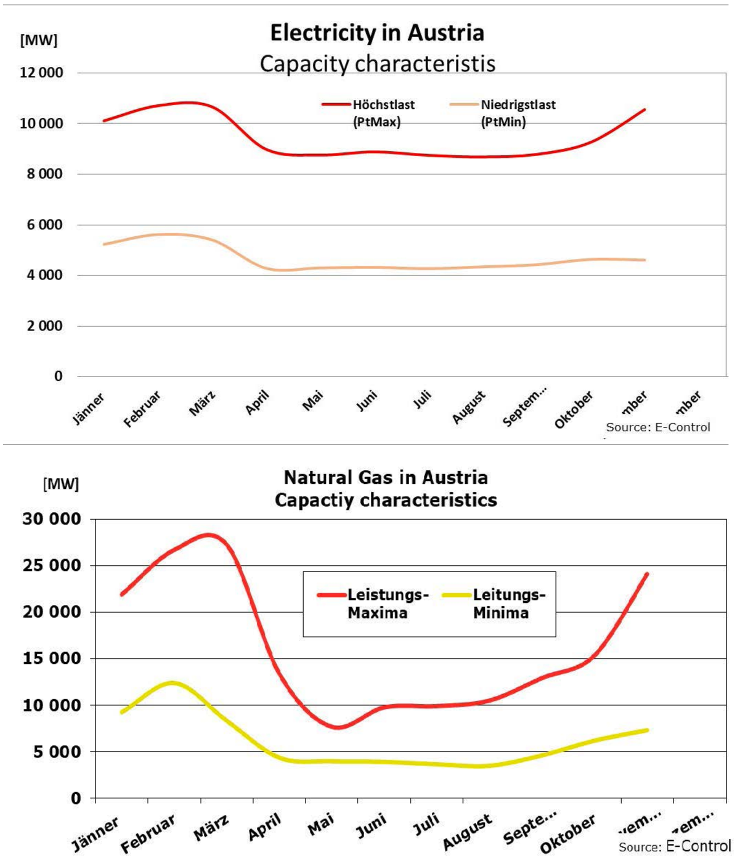
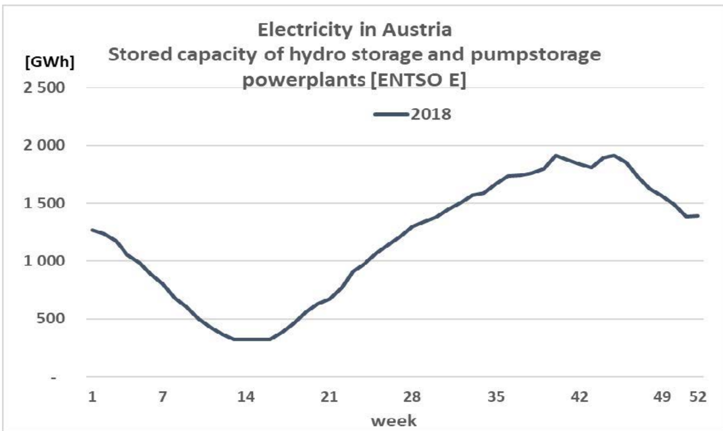


Figure 47: Maximum and minimum load of Austrian electricity grid compared to the gas grid; © E Contro 2018.



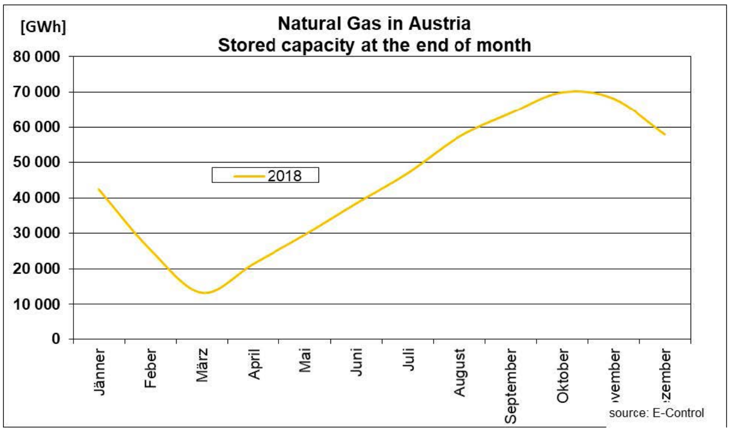


Figure 48: Maximum available capacity of pump hydro storage compared to gas storage within caverns per week; © ENTSO E, E-Control 2018.

Natural gas is a fossil fuel. If it is burned, additional GHG is released into the atmosphere. In the light of the Paris Agreement, the gas grids need to switch to renewable energy just as the electricity grids are required to do. The predominant and most promising technique available to achieve this is upgrading biogas to biomethane.

Before biogas can be injected into the gas grid, it needs to be purified and components which are not allowed to be injected into the gas grid must be removed. These components are mainly the water content, sulphur and nitrogen compounds, oxygen and siloxane. Additionally, the requisite caloric value and Wobbe Index need to be achieved by eliminating carbon dioxide. Table 22 shows the typical components of biogas and the requirements for gas grid injection.

Component		Biogas [$\%_{vol.}$]	Requirements for gas grid injection in Austria	
			ÖVGW G 31	*ÖVGW GB 220*
Methane	[CH_4]	50 – 70		≥ 96 $\%_{mol}$
Carbon dioxide	[CO_2]	30 - 50	≤ 2 $\%_{mol}$	
Higher heating value				≥ 10.7 kWh_{Hs} Nm^{-3}
Wobbe Index			≥ 13.3 kWh_{Hs} Nm^{-3}	
Nitrogen	[N_2]	0 - 5	≤ 5 $\%_{mol}$	
Sulfur (total)	[S]		≤ 10 mg m-3	
Hydrogen Sulfide	[H_2S]	0 - 2	≤ 5 mg m^{-3} short term up to 30	
Hydrogen	[H_2]	0 - 1	≤ 4 $\%_{mol}$	
Oxygen	[O_2]	0 - 1	≤ 0.5 $\%_{mol}$	
Ammonia	[NH_3]	0 - 2	0	
Dew point		saturated	≤ -8 at 40 bar	
Siloxane				≤ 5 mg m^{-3}

Table 22: Components of raw biogas versus requirements for gas grid injection within Austria; © ÖVGW G31 and GB220.

The flow speed, caloric value and other properties of different gasses vary according to their components and densities. The Wobbe Index is an important indicator of gas character which, along with the caloric value of the gas, is of particular relevance for gas installations. It expresses the convertibility of different gases so that they can be used with the same gas burner without the need to change the burner nozzle. The Wobbe Index is calculated by dividing the higher heating value of the gas by the root of its relative density (with respect to air) :

$$Ws = \frac{Hs}{\sqrt{\frac{gas\ density}{air\ density}}}$$

Every gas-burning device has the Wobbe Index included on its labelling.

Components		[%]				
Methane	[CH_4]	**90**	**92**	**94**	**96**	**98**
Carbon dioxide	[CO_2]	8,17	6,17	4,17	2,17	1,17
Nitrogen	[N_2]	1,5	1,5	1,5	1,5	0,5
Oxygen	[O_2]	0,03	0,03	0,03	0,03	0,03
Hydrogen	[H_2]	0,3	0,3	0,3	0,3	0,3
Hydrogen Sulfide	[H_2S]	0	0	0	0	0
total		100	100	100	100	100
Wobbe Index	**[kWh_{Hs} Nm^{-3}]**	**12,5**	**12,9**	**13,4**	**13,9**	**14,4**
	[MJ_{Hs} Nm^{-3}]	**44,9**	**46,6**	**48,4**	**50,2**	**51,9**

Table 23: Typical Components within biomethane and their impact on the Wobbe Index; © AKBOE 2020.

10.4.1 PURIFICATION

The purification of biogas usually includes desulphurisation, drying and the separation of carbon dioxide.

DESULPHURISATION

The hydrogen sulphide content in the biogas depends on the feedstock used. Hydrogen sulphide itself has corrosive properties; on combustion, however, it also produces sulphur dioxide, which builds up on sensitive components and is an environmental pollutant causing acid rainfall. H_2S usually occurs in biogas at a higher concentration than the upper limit value for gas grid injection, which means it must be at least partially removed. The amount of oxygen permissible in biomethane, as well as concentrations of nitrogen and sulphur compounds, is strictly limited; overly high levels of these impurities would also lower the caloric value and the Wobbe Index. The desulphurisation technique used is therefore different, according to whether the biogas is to be used directly for CHP or further upgraded to produce biomethane. If the gas is to be upgraded to biomethane, oxygen instead of air is used for biological desulphurisation; air contains a high level of nitrogen, which should not be present in pure biomethane. In addition, desulphurisation is usually carried out in more than one step. It is often a combination of several of the following steps:

- Chemical desulphurisation in which doses of iron salts are added into the liquid phase of the digester
- Biological desulphurisation with oxygen in an external column
- Adsorption on activated carbon

DRYING

When it forms, biogas is saturated with water vapor and reaches the dew point every time it is cooled, producing water. The occurrence of water within the gas grid needs to be avoided because it could accumulate at the lowest point of the gas grid and cause pressure variation. Additionally, it could cause damage to application devices such as an internal combustion engine. A range of dewatering techniques are used to meet the requirements, including:

- Condensation via cooling
- Adsorption with zeolites, silica gels or aluminium oxide
- Absorption with glycol

The most common technique for dewatering the biogas is to cool it with a cooling aggregate. The carbon dioxide removal step, such as pressure swing adsorption, also removes water; this can be thought of as back-up dewatering. Adsorption with zeolites, silica gel or aluminium oxide is carried out in two alternately pressurised vessels.

CARBON DIOXIDE REMOVAL

Carbon dioxide removal must be carried out in order for the gas to reach the minimum level of caloric value and Wobbe Index for gas grid injection. The choice of technique is governed by several parameters, including the required methane content, energy demand, the required gas grid pressure, the existence of wastewater, maximum methane losses etc. The most commonly used techniques for carbon dioxide removal are:

- Pressure swing absorption
- Water scrubber
- Chemical absorbance
- Membrane technique

Pressure Swing Adsorption (PSA)

Pressure swing adsorption is a proven method of separation and has been used for decades – first in the gas industry and subsequently, after adaptation, for biogas processing.

The essential component for separating the gases is a column filled with activated carbon, zeolitic molecular sieves or carbon molecular sieves. These substances have the requisite characteristics for trapping carbon dioxide, including a large surface area and a particular pore size. Usually two columns work directly together; to achieve a continuous process, PSA devices comprise at least 4 and sometimes as many as 8 columns.

When biogas is fed into the first PSA column, the pressure increases and the activated carbon physically adsorbs CO_2 while methane passes through the process and exits at the top of the column. The moment the activated carbon has reached a full load of carbon dioxide, the raw biogas inlet to that column is closed and the next lot of biogas is fed into another column, installed in parallel, which also containsactivated carbon. In order to remove the carbon dioxide from the acitivated carbon once it has become saturated, the gaseous content of the column in question is partly fed into another column, also containing activated carbon, until the two columns have reached nearly equal pressure.
This lower pressure level releases the carbon dioxide from the activated carbon, and it can then be removed with a vacuum, after which the column is ready to begin the process again and separate carbon dioxide from the next batch of raw biogas. These connected steps are necessary to achieve a high methane content in the purified biomethane, to guarantee low methane losses and to avoid unwanted high energy demand. At least four vessels must be involved for a continous operation. A positive effect of this process is that other unwanted gases, such as H_2S, are also retained by the activated carbon and, in addition, the process dries the gas. If H_2S starts to pass unhindered through the process, maintenance needs to be carried out on the activated carbon or it must be replaced. In order to prevent the lifetime of the activated carbon from becoing too low, fine-cleaning must be carried out to remove H_2S before the biogas is pumped into the adsorption column.

The level of methane loss is mainly dependent on the design of the system. Any CH_4 in the exhaust gas must be burnt because of its status as a greenhouse gas.

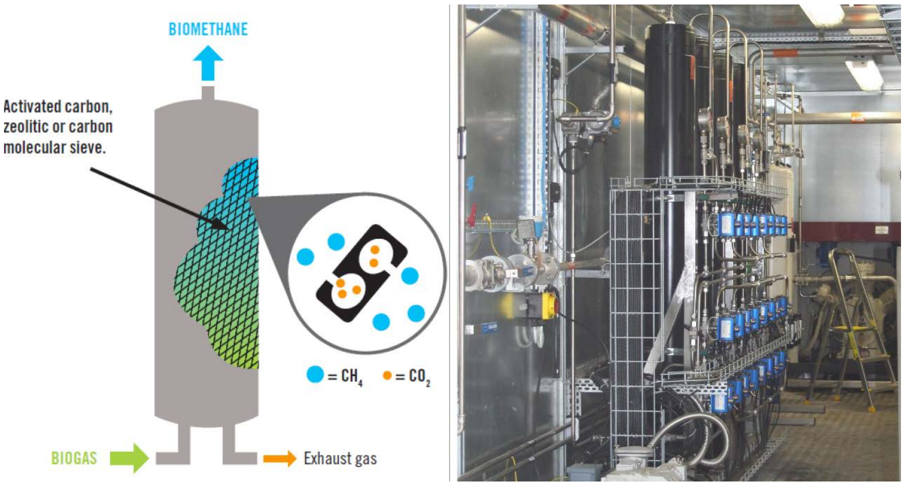


Figure 49: Left: Detail of a CO_2 separation vessel with activated carbon in a Pressure Swing Adsorption device (PSA); © Fachverband Biogas 2017, right: PSA column.

Water scrubbing

We all know this effect from our sparkling beverages: at low temperatures and under light pressure, carbon dioxide is soluble in the liquid. By releasing the pressure, for example by opening the beverage bottle, carbon dioxide is released. Heating the liquid further reduces the solubility of carbon dioxide. Water scrubbing uses this well-known principle and the different solubilities of carbon dioxide and methane in water. In the first step, water droplets and other bigger impurities are removed from the biogas, which then flows at a pressure of 4 to 10 bars into the scrubber column. The gas enters the column at the bottom while cold water flows in at the top, in counterflow. Carbon dioxide, hydrogen sulphide, ammonia and particulates are dissolved in the water and methane-rich biomethane can be extracted at the top of the column. For gas grid injection, the biomethane must then be dried. At the bottom of the column, carbon dioxide-rich water with a low methane content is conveyed to the flashing tower. In order to retain the dissolved methane, the pressure is removed as a first step, allowing dissolved methane to escape from the water and be directed back into the process again. After this, the exhaust gas-rich water is directed into the flashing tower where the CO_2 etc. is released by lowering the pressure to ambient air pressure, while air is pressed inside from the bottom. H_2S dissolves very well in water, so as long as the hydrogen sulphide content of the biogas was not too high, water scrubbing usually produces an upgraded gas within the maximum limits for H_2S and ready to be injected into the gas grid without any further treatment. Depending on the methane content in the exhaust gas, an additional post-process combustion step may be needed.

Component		Solubility in water at 1 bar partial pressure of dissolved gas [mmol/kg bar]	
		0 °C	25 °C
Methane	[CH_4]	2.45	0.72
Carbon dioxide	[CO_2]	75	34
Ammonia	[NH_3]	53,000	28,000
Hydrogen Sulfide	[H_2S]	205	102
Air		1.27	0.72

Table 24: Solubility of different gases at 1 bar and different temperatures within water; © Tretter H. 2003.

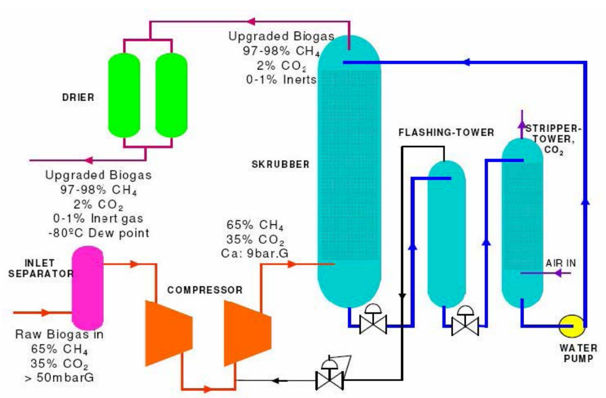


Figure 50: Scheme of water scrubbing technique; © Tretter H. 2003.


Picture 70: CO_2 separation through water scrubber left: scrubber column, right: water scrubber technique installed in a container.

Physical scrubbing

Carbon dioxide removal through physical scrubbing is also based on the different solubility of gases in fluids. The process is very similar to water scrubbing, except that an alternative solvent is used rather than water. CO_2 dissolves more readily in polyethylene glycol (brand: Selexol) than in water, which is an obvious advantage. The process consequently requires less pressure and smaller columns p to provide an equivalent level of performance to a water scrubber. The downside is that it is more difficult to regenerate the solvent. Heat is usually needed to separate CO_2 from the solvent after the scrubbing process.


Picture 71: CO_2 separation through physical scrubber, left: scrubber column, right: physical scrubber installed in a container.

Chemical scrubbing

Chemical scrubbing is similar to physical scrubbing; the main difference between physical scrubbing and chemical scrubbing technologies is that for the latter, the affinity for CO_2 is even higher. The chemical scrubbing process is consequently very highly selective . The purity of the resulting gases is very high: a methane concentration above 99.9% and methane losses under 0.5% are possible. Another advantage is that the scrubbing columns can be operated at atmospheric pressure, whereas all other biogas upgrading technologies are operated with pressurised columns. The disadvantage is that the recovery of the detergent needs to be carried out with heat; this is easier if there is a source of exhaust heat nearby. Chemicals used include monoethanolamine (MEA) and methyldiethanolamine (DEA).

Membrane separation technique

Membrane separation technique uses the different permeability and size of various gaseous molecules to separate gases using specially conditioned membranes. These membranes are 20 times more permeable for CO_2 than for CH_4. The membranes are formed into hollow fibres, which are bundled together in a steel column. Depending on the required level of performance, several columns can work in parallel.
To achieve a high methane content in the purified gas and avoid an excessive amount of methane in the exhaust gas, the membrane separation technique is usually applied in a two- or three-stage process. Nitrogen does not diffuse through the membrane wall and therefore remains together with the methane, making it important to avoid any accumulation of nitrogen in the biogas. Biogas needs to be dewatered, de-oiled and desulphurised very thoroughly before entering the membranes to avoid causing excessive wear.

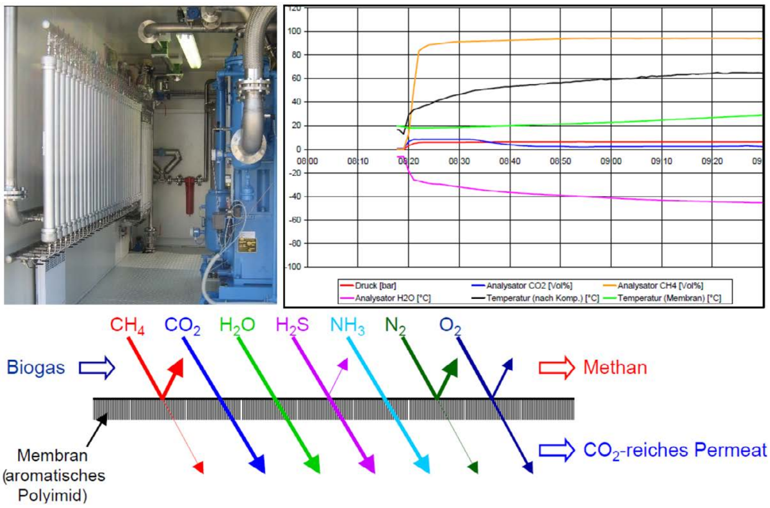


Figure 51: Top left: CO_2 separation through membrane technique, top right: ramp up curve after start, bottom scheme of membrane technique; © top right & bottom: © Harasek, 2009.

The choice of upgrading technique depends on several factors, including:

- Plant size
- Required pressure after purification
- Maximum methane content in the purified gas
- Availability of waste heat
- Availability of wastewater
- Availability of maintenance services

Upgrading technologies have developed hugely in the last two decades. Installations have changed according to the requirements of their specific set-up and regional location, but also through more general technological advance and the evolution of legal requirements. Today there are about 500 industrial installations upgrading biogas to biomethane. A great deal of experience of this technology has been gained over the last 20 years: biogas upgrading is now a well-established process using state-of-the-art technology.

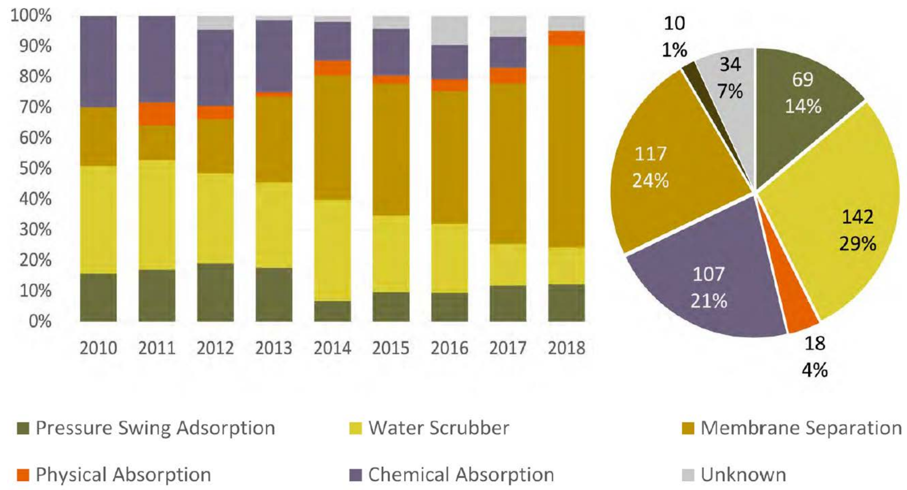


Figure 52: Relative use of upgrading techniques, left: worldwide, right: Europe; © EBA, DMT 2020.

11 SPECIAL CASE: HOUSEHOLD BIOGAS SYSTEMS

Biogas systems can be built to nearly any size. The volume of the digester can range from below 1 m^3 up to several thousand m^3. The previous chapters have dealt with biogas technology on a larger scale, often referred to as industrial or commercial size. This chapter is about small-scale biogas production, sometimes referred to as domestic biogas, home digesters or household biogas systems.

In terms of the overall number of installed biogas plants throughout the world, small scale digesters are by far the most common.

There are a number of definitions of household biogas systems. The most universally accepted definition is probably the one set out by the International Organisation for Standardisation (ISO 20675), which defines a 'household scale biogas system' as a:
'biogas system with a production capacity of biogas having an energy content of 1 MWh – 100 MWh per year'. This equals about 11 kW_{th} full load capacity.

As a very rough estimation, it can be assumed that for each m^3 of active digester size, about 0.25 kW_{th} of biogas can be continuously produced. Hence, the digester size of a domestic biogas system is below 45 m^3.

11.1 INCIDENCE WORLDWIDE

There is no reliable data on the number of household biogas systems installed worldwide, although very rough estimates have been published by several sources.
In China, there is an estimated total of 40 million domestic systems. India[3] is home to approximately 4.5 million domestic biogas systems, and Vietnam had installed more than 100,000 systems by 2010. Further Asian countries to be highlighted are Cambodia, Laos, Indonesia, and Nepal (225,000 by 2011). In Africa, where anaerobic digestion is less prevalent, countries like Kenya (about 20,000 installations by 2019) and Uganda (approximately 7,500 by 2017) are amongst the frontrunners in terms of domestic biogas installations[4]. Several thousand small biogas plants for rural households are in operation in Latin America.

11.2 REASONS FOR INSTALLING HOUSEHOLD BIOGAS SYSTEMS

There are many reasons to support and install household biogas systems, including:

- **Own energy production.** In vast areas of the world, energy supply is still a challenge. Energy costs money and time and causes GHG emissions (see points below). Private production of renewable energy, e.g. for cooking or lighting, via a domestic biogas plant, helps people to avoid the need to buy or collect fuel.
- **Energy production saves money.** Many people need to spend a substantial amount of their money on firewood, charcoal or other fuels like LPG or kerosene. If they operate a household biogas system and produce their own energy, they can save money.
- **Deforestation.** In many areas of the world people depend on firewood to cook their meals. The forests in these areas are often not managed in a sustainable way. People cut down more trees than are replaced through annual growth. The consequence is deforestation. Household biogas systems can be a part of the solution because the people who need energy to cook can then produce fuel by themselves, reducing the need to fell trees.
- **Health.** Indoor cooking with firewood on open fireplaces causes high emissions of smoke, soot and particles. The inhalation of these gases and particles causes diseases, such as lung disease and eye irritation. Biogas produces much lower emissions when it burns, meaning that preparing meals with biogas has a positive effect on health.
- **In the event of firewood shortage, people often burn dried cow dung.** The higher ammonia emissions also cause eye irritation and important nutrients such as nitrogen are emitted into the air and lost.
- **Time saving.** Collecting firewood often takes up a substantial amount of time for woman and children. By using feedstocks that are often available close to the house, and digesting them to produce biogas, a considerable amount of time can be saved.
- **Greenhouse gas (GHG) emission reduction.** The domestic production of biogas and its use as fuel has several positive effects on GHG emissions:
  - > CO_2 emissions are avoided by replacing fossil fuels.
  - > The avoidance of deforestation in regions where forests are not used sustainably means that the CO_2 emissions that occur through deforestation are also avoided.
  - > Stored organic material (for example landfilled kitchen waste or animal excrement) emit methane. By processing these materials in a gastight biogas system and burning the biogas, GHG emissions can be avoided.

> The GHG emission reduction depends greatly on the gastight nature of the household gas system, however. The biogas produced consists mainly of methane, which has a very high GHG potential. If the digester is not gastight, the biogas plant can cause environmental damage; for this reason, the household biogas system must be as gastight as possible![5]

- **Fertiliser.** (Nearly) all nutrients that are fed into the system with the feedstock will remain in the digestate and can be used for fertilising plants. Additionally, organic bound nutrients are mineralised during digestion, meaning that plants can assimilate them much better. The digestate is therefore a very valuable fertiliser. It is often reported that fertilising the fields with digestate leads to improved crop yields (Gilbert, J. 2019 and Wilken, D. (2018).
- **Sanitisation.** Many kinds of bacteria are reduced when being processed in a biogas system, especially potential pathogens. The reason is that the bacteria belonging to the AD system are optimally adapted to the growing conditions and the feedstock inside the digester, whereas potential pathogen bacteria are not and cannot compete with the AD bacteria. Many studies show this sanitisation effect (Fachverband Biogas, Hintergrundpapier Hygiene, 2019). There are only a limited number of feedstock categories which might cause problems, for example, meat products or slaughterhouse waste. These need to be sanitised before being used as feedstock in domestic biogas plants and should not be added to the digester without a sanitisation step. All vegetable feedstocks can be used in a biogas digester without any risk of pathogen bacteria. In some cases, human excrement is digested. Again, the process has a sanitisation effect by reducing potential pathogen bacteria.
- **Weed control.** There are usually many viable weed seeds in animal manure or dung. If the farmer is fertilising her/his fields with non-digested manure, many seeds are spread upon the fields again, requiring the farmer to use herbicides or invest many hours in weed control. In a biogas system, many weed seeds are digested and/or deactivated (see chapter 8: digestate storage and use).

11.3 CHARACTERISTICS OF A HOUSEHOLD BIOGAS SYSTEM

The household biogas installation consists mainly of a digester tank with an inlet for the feedstock and an outlet for the digestate. The outlet is often constructed as an overflow. The gas is produced in the liquid, which fills most of the digester volume. The gas volume/storage is usually in the upper part of the digester. Sometimes an external balloon serves as gas storage. From the gas storage, a hose takes the generated biogas out of the system. The gas is

compressed by simple methods, like stones on the digester or height of water, but usually not by compressors. Because many domestic biogas systems are installed in warmer climates, they are not generally equipped with a heating or stirring system. In colder climates, some systems are surrounded by a simple green house. The mechanical parts (if there are any) are usually very simple, robust and not electronically driven. The hydraulic retention time must be high to allow sufficient biogas yields.
The daily input is only a few kilograms. The feedstocks used are animal excrement, harvest residues (e.g. un-saleable fruit or plant leaves) or food waste, especially if food is vegetarian. Food waste containing meat might allow the growth of pathogen bacteria. The feedstock used should be liquid or at least diluted (e.g. manure or foodstuff, which is diluted in the digester) and free of bigger particles (e.g. no branches of trees). Waste that might be contaminated with pathogen bacteria (like slaughterhouse waste) should not be used, because domestic biogas plants do not have a sanitisation unit.
The amount of biogas produced is low (a few m^3 per day). The digester volume can be anything from just a few m^3 up to 45 m^3, although it is usually at the smaller end of this range. The technology is relatively cheap and simple. It is advisable to wash the biogas before it is used, e.g. by letting it flow through a bottle filled with water.
Construction and operation are relatively simple; however, experience shows that local knowledge and clear responsibilities are key for a successful, long-term operation.

11.4 TYPES OF DIGESTERS

There are three types of domestic digesters – fixed dome digesters, floating drum digesters and plastic bag digesters (Wilken, D. 2019).

11.5 FIXED DOME DIGESTERS

Probably the most frequently installed type of digester is the fixed dome digester. They have a long history and were invented in China; because the majority of household biogas systems in the world are installed in China, fixed dome digesters are the prevalent small-scale digester type worldwide.
In a fixed dome digester, the gas holder is placed at the top and the bottom contains the liquid. As gas is produced, the liquid is displaced into a compensation tank and gas pressure increases according to the volume of gas stored and the height difference between the liquid level in the digester and the liquid level in the compensation tank. Because fixed dome digesters have no moving parts, they are fairly inexpensive and they are well-suited to warm or medium temperature areas. They are often constructed partially underground. Another advantage is that they can be made of local materials, e.g. bricks. A disadvantage is that the gas-tightness (protecting against methane emissions!) and resistance to corrosion

is questionable. With long-term operation the construction materials often corrode (H_2S and water combine to form sulphuric acid) and cracks can occur. If there are gas leakages, the GHG balance is questionable and, in some cases, these installations are causing environmental damage.[6] The digestor wall must therefore be regularly monitored for cracks.

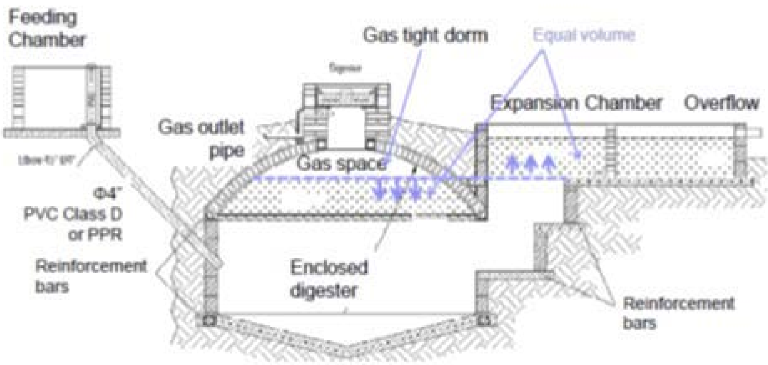


Figure 53: Fixed dome digester. Source: Akut Umweltschutz.

11.5.1 FLOATING DRUM DIGESTERS

Floating drum plants consist of an underground digester (cylindrical or dome-shaped) and a moving gas-holder. The floating drum moves up and down depending on the amount of gas it is storing, meaning it indicates the amount of gas being stored. In order to increase the gas pressure, stones are often placed on top of the inner drum. This type of digesters is popular in India.

Picture 72: Floating drum digester. Source: German Biogas Association.

Picture 72 shows two black drums. The white tube in the foreground is the outlet, constructed as an overflow. If, for example, 1 litre feedstock is fed in, about 1 litre liquid will flow out. In the case shown in the picture, the digestate is collected in flowerpots (at the bottom of the picture 72). The water evaporates and fertiliser (of a consistency similar to soil) remains.
The most common negative aspect of floating drum digesters is that methane emissions can occur via the gap between the inner

and the outer drum (see Picture 73). The gap should be as small as possible but still wide enough to let the inner drum float up and own.

Picture 73: Gap between the inner and outer tube. Source: German Biogas Association.

11.5.2 PLASTIC BAG DIGESTERS

Plastic bag digesters were developed only recently. As the name indicates, they are mainly constructed in form of a plastic bag (made of special membranes like EPDM). The bag serves as digester, holding the liquid, and in some designs also as a gas holder in the upper part. Other systems use gas storage in the form of an external balloon. Plastic bag digesters are not usually equipped with a heating system or mixers, although a design with a simple stirring system is available (see Picture 74). Feedstock is fed into a plastic bag where the biogas is produced. This system has several advantages: it is relatively robust, gas- and liquid-tight, and the material is resistant to corrosion.

Picture 74: Plastic bag digester, Source: Ökobit.

11.6 BIOGAS USE

Biogas can be used as a direct energy source for cooking stoves. This is very popular in developing countries where people often have to spend hours each day collecting firewood for cooking or where other energy sources, such as LPG or charcoal, are too expensive.

Small household biogas systems can provide a reliable source of biogas that can be fed directly into a cooking stove. Cooking stoves that burn biogas also provide a much cleaner exhaust gas which improves the indoor air quality for families that previously relied on firewood or other less pure fossil fuels, such as diesel, kerosene or LPG (United States Environmental Protection Agency, 2008). The biogas can also be used directly in a gas lantern to provide a steady source of lighting.
Due to the low energy output, household biogas systems are seldom used for electricity production.

11.7 THE SITUATION IN EUROPE

Most European biogas manufactures deal only with biogas systems on a larger scale. There are almost no officially approved domestic biogas installations in Europe; only a few digesters are run for private domestic use. There are a number of reasons for this.
The conditions that must be met to obtain approval or be granted a permit vary hugely across Europe. There are significant variations between regions, countries and even at a local level. In some countries, domestic biogas systems are not accounted for at all, or the requirements are unclear. Approval is usually dependent on compliance with a number of standards, which are not easily met, such as emission control (to avoid or limit emissions into air, soil and water), safety (safety distances, fencing, etc.), operation (e.g. qualification of operator), controlled use of the digestate and several other issues.

European households are usually reliably connected to the energy network (electricity, gas and/or heat), meaning there is little need for energy self-sufficiency, although a number of people are interested in the principle.

In Northern Europe and areas where the wintertime is cold, household systems might not work well without a heating system, which is not usually installed for domestic biogas production.

A household biogas system can be set up at low cost, which is one essential advantage in developing countries. However, the amount of energy produced is low as well.

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NOTES

1 Methane has a very high GHG potential.

2 For example, a biogas plant with a size of 500 kWe has a biogas production rate of about 250 m³ per hour. If 6 hours-worth of biogas production must be stored, e.g. during maintenance of the CHP, the capacity of the gas storage should be 1,500 m³.

3 Source, the Indian Biogas Association.

4 The main source for this paragraph is “Biowaste to Biogas”, published by the German Biogas Association (Fachverband Biogas) in 2019. Additionally, several expert opinions from the German Biogas Association are included.

5 This is of course true for all biogas plants, whether on an industrial or a domestic scale.

6 This is equally valid for both domestic and industrial biogas plants.

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About DiBiCoo

We facilitate collaboration between European biogas industries & stakeholders from emerging and developing markets through the development and application of innovative digital and non-digital support tools, knowledge transfer and capacity building.

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