Overview and Categorization of European Biogas Technologies

- Anaerobic Digestion -

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DiBiCoo – Digital Global Biogas Cooperation
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Executive Summary of D 2.2

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

The structure following the introduction section about Anaerobic Digestions (AD) follows the biogas processing logic: from feedstock storage on site and necessary pre-treatment to the various digester technologies. Special chapters on important elements of any biogas plant are elaborated in detail (e.g. on measurement, control and regulation technologies).

Upgrading biogas to biomethane quality as well as various application of Biogas are introduced (e.g. its GHG mitigation potential, as Combined Heat & Power (CHP) plants).

Due to the huge amount of existing information and knowledge on this topic it may occur that not everything is included or considered extensively. We propose this deliverable as a solid starting point getting to know about anaerobic digestion. This doesn´t replace special training courses and at least professional planning.

The detailed descriptions of certain technologies are not implying any preference to a technology, service provider or device. Similarly, pictures including company names shall not be seen as a preference to any specific company or technology. It is done for visualization purposes only.

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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 call 'Market Uptake Support'.

The target importing emerging and developing 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 months-timeline and a budget of 3 Million Euros. It is implemented by the consortium and coordinated by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

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 mutually benefit importing and exporting countries through facilitating dialogue between European biogas industries and biogas stakeholders or developers from emerging and developing markets. The consortium works to advance knowledge transfer and experience sharing to improve local policies that allow increased market uptake by target countries. This will be facilitated through a digital matchmaking platform and classical capacity development mechanisms for improved networking, information sharing, and technical/financial competences. Furthermore, DiBiCoo will identify five demo cases up to investment stages in the 5 importing countries. Thus, the project will help mitigate GHG emissions and increase the share of global renewable energy generation. 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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Content

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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 where microorganism decompose organic matter generating two very valuable products, renewable energy called biogas and digestate. In nature, this is a well-known process which takes 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. Compared to the latter, anaerobic digestion offers the possibility to 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 anaerobic digestion process can be divided into four stages which follow each other but usually take place simultaneously in the digester:

- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

Within the first process step, the **hydrolysis,** hydrolytic bacteria break complex organic matter (carbohydrates, fats and proteins) down into simple organic compounds like monosaccharides, fatty acids and other amino acids. Fulfilling their task, hydrolytic bacteria produce enzymes to decompose the organic matter. The hydrolytic bacteria like a pH value between pH 5 to pH 6 and additionally, the produced enzymes have usually also their pH value optimum below pH 7.

Within the second step -the first fermentation process- the **Acidification**, fermentative bacteria further break down the products from first step into lower fatty acids like propionic-, butyric-, valeric acid, carbon dioxide and also in smaller amount alcohols, H_2S and lactic acid. The optimal pH value for acidogenic bacteria lies also between pH 4 to pH 6.

The third step, the **Acetogenesis**, forms mainly from propionic acid and butyric, through acetogenic bacteria, acetic acid, hydrogen and carbon dioxide. A too high hydrogen partial pressure may hinder acetogenic bacteria in their activity and so amount of propionic acid and butyric may raise and cause a process disturbance.

The last step, the **Methanogenesis**, builds the biogas through methanogenetic archaea. From all four steps this is the most sensitive step and the involved archaea has the longest doubling time.

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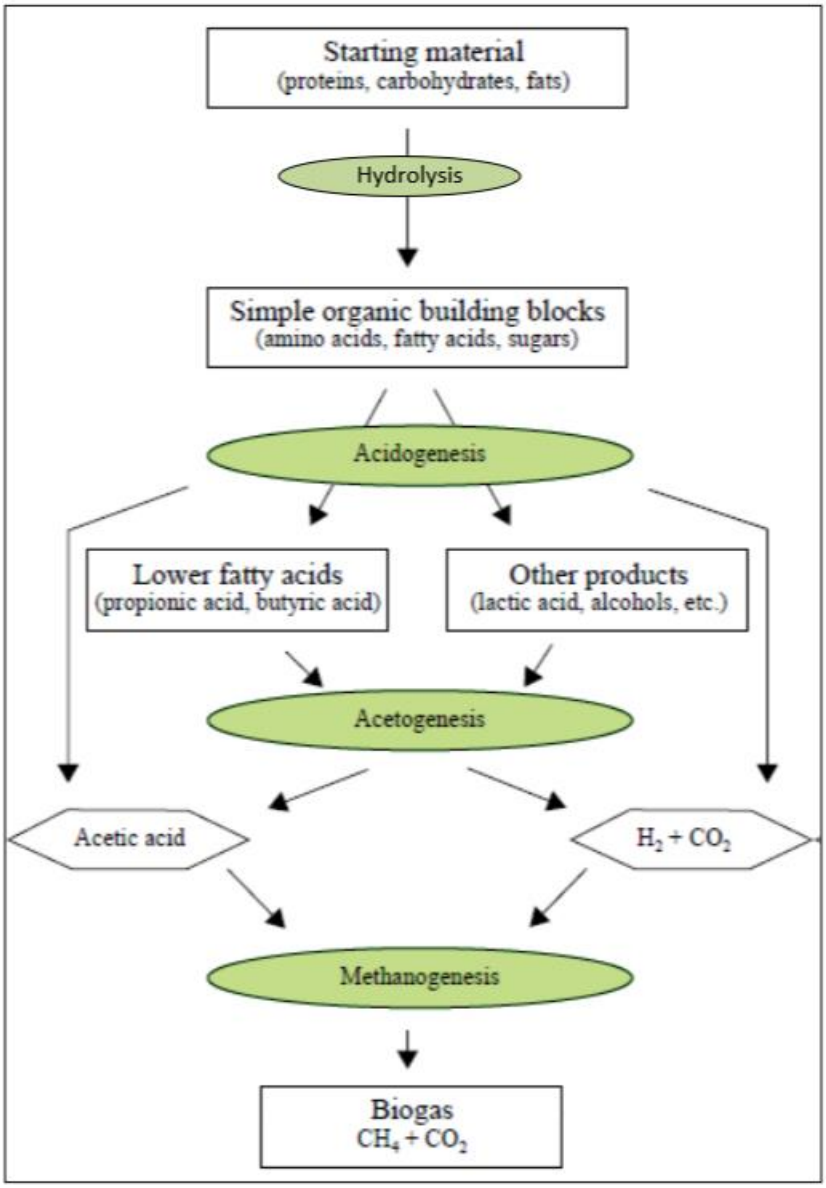

Figure 1: Scheme of the decomposing process of organic matter within AD; © FNR 2012.

Although these four steps and their involved bacteria are simultaneously active, they have some very different requirements and behavior. Table 1 gives a short overview of the different requirements of involved bacteria within anaerobic digestion.

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

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 shows that to some extent it poses difficulties to the overall anaerobic digestion process if the four individual process 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 the sensitive ones who do not like temperature changes of more than 1 °C per day, are very sensitive to light and oxygen and at least stop working at pH values below 6.5. The latter, in combination with the doubling time of bacteria, is one of the main reasons for the biogas process to stop. Additionally, the methanogenic archaea have a higher need for several micronutrients such as cobalt, nickel, molybdenum, selenium, copper and zinc. Copper and Zink are usually not in shortage if e.g. manure is used as feedstock. The recommended amount of trace elements is shown in Table 2. These recommendations on the amount of trace elements vary highly and show the difficulty to optimize a process based on living organism. The same can be said about the optimum ratio of macro elements. The ideal ratio of *C:N:P:S* shall reach 600:15:15:3, but it has to be considered that already the range of *C:N* differs from 10-30:10 (Paterson, 2012; Schulz 2006).

The following sections provide more details on a selection of factors impacting the AD process.

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

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	

1.1 Inhibitors

Table 3 shows several inhibitors who can hinder the digestion process. As the inhibition process depends on many circumstances, these figures cannot be seen as strict concentrations and not consider all possible inhibitors that may occur, but shall give an overview and demonstrate how sensitive and important substrate receipt and precheck is. For example: products with high protein content can cause N-inhibition through its high nitrogen content. High amounts of Volatile Fatty Acids (VFA) can be both a secondary effect when methanogenic archaea are inhibited by other inhibitors and thus no longer consume the VFA, or can be due to overfeeding of the biogas reactor and therefore too low pH value.

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

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

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

	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

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1.2 Temperature profiles

Depending on the temperature of the digestion process, there are defined three main temperature windows for anaerobic digestion (see Table 5): psychrophile, mesophil and thermophil. Within each temperature zone special bacteria have their optimum of productivity. The closer the temperature to the optimum in each zone, the better is the process. The higher the temperature, the faster is the process, but in total not more biogas will be generated (Figure 2). As thermophilic bacteria are more sensitive to temperature fluctuation, temperature control must be well installed and exact temperature secured. Additionally, these bacteria do not allow a too high ammonia concentration within the substrate, although they can be adapted slowly to a higher content.

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

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

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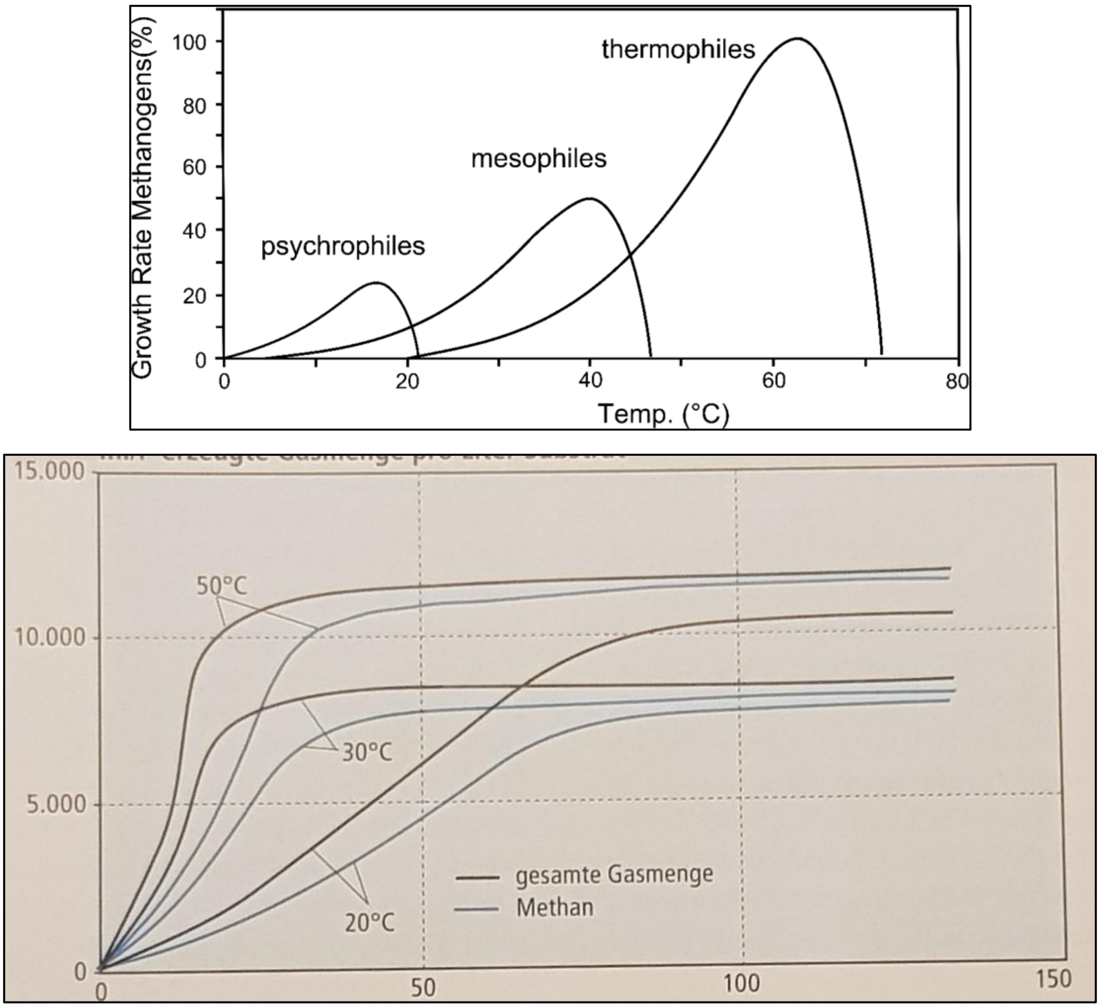

Figure 2: Growth rate of methanogenic bacteria at different temperature profiles and biogas (ml l^{-1}) forming potential depending on temperature and retention time (days); © Baader, Schulz 2006, 1978, Van Lier 1997.

1.3 Organic loading rate and retention time

Besides the chosen temperature and other factors, the organic loading rate and the retention time of feedstock within the digestion process are usually the main figures for plant design. As the organic matter differs often between years or even seasons and from feedstock to feedstock, it is critical to find the optimum of digester size, to make sure that decomposition of degradable organic matter will happen completely, and maximum biogas yield will be achieved. The organic loading rate (OLR) expresses the kilogram volatile solids fed per day and per m³ digester volume into the digester. In comparison to the OLR the hydraulic retention time (HRT) gives the relevant information on how long the feedstock will theoretically stay in the digestion process. The HRT is calculated by dividing the daily fed feedstock expressed in m³ through the active digester volume. Figure 3 shows the link between loading rate and retention time depending on volatile solid content of used feedstock.

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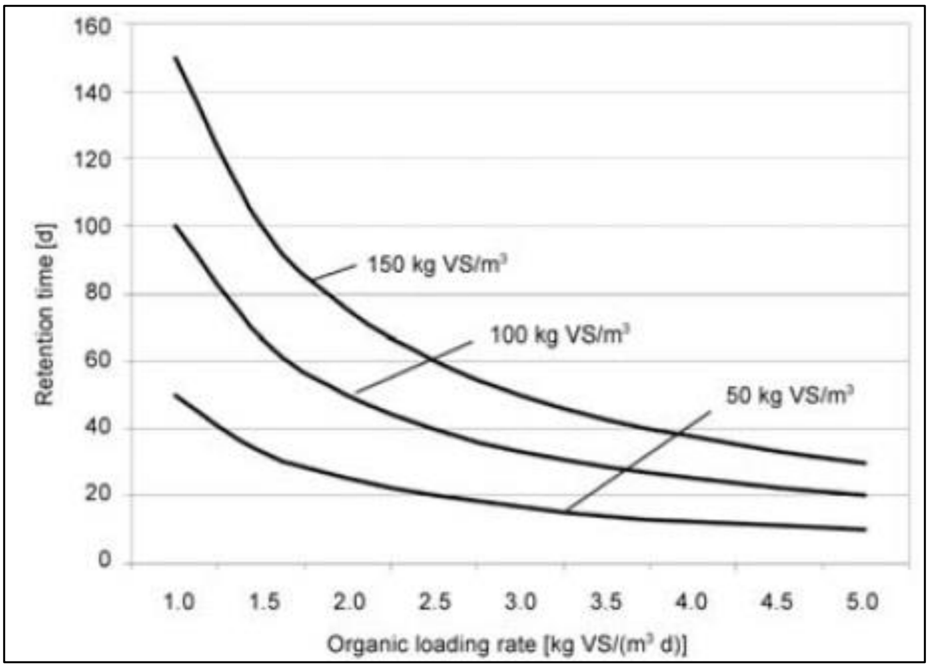

Figure 3: Correlation between organic load rate (OLR) and hydraulic retention time (HRT) depending on volatile solid content of feedstock; © Paterson 2012.

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 through methane production per m³ digester volume. This figure can only be compared between digestion systems if the same feedstock is used. Therefore, the equation is not very frequently used.

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.

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

In comparison to the productivity of the digester, the methane production (Equation 4) informs about the methane yield per ton volatile solids and is a commonly used parameter.

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Equation 4: Methane yield per ton volatile solids expressed in $Nm^3\ t_{VS}^{-1}$, $V_{(CH4)}$= methane production expressed in m^3 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 gives the information about the degradation of volatile organic solids within the digestion process. Therefore, it gives information on 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

Depending on the digestible carbon content of feedstock, the composition and yield of raw biogas differ. Table 6 and Table 7 give an overview of potential biogas yields of biodegradable components and common substrates used in biogas plants. As these figures depend greatly on the exact volatile solids content and other factors, these figures can only be approximate numbers. For detailed planning on special feedstock, in-depth batch analysis is always recommended.

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

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

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

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

1.6 Plant design

While physical parameters of the feedstocks will determine the required technology (dry/wet digestion, required pre-treatment technologies etc.) the chemical parameters will determine the amount of biogas produced. The general design of the plant configuration is usually similar in each biogas plant. It differs only due to different requirements of the used substrates. Another differentiation can be made regarding the possible further treatment of digestate and most importantly, regarding the further application of biogas.

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

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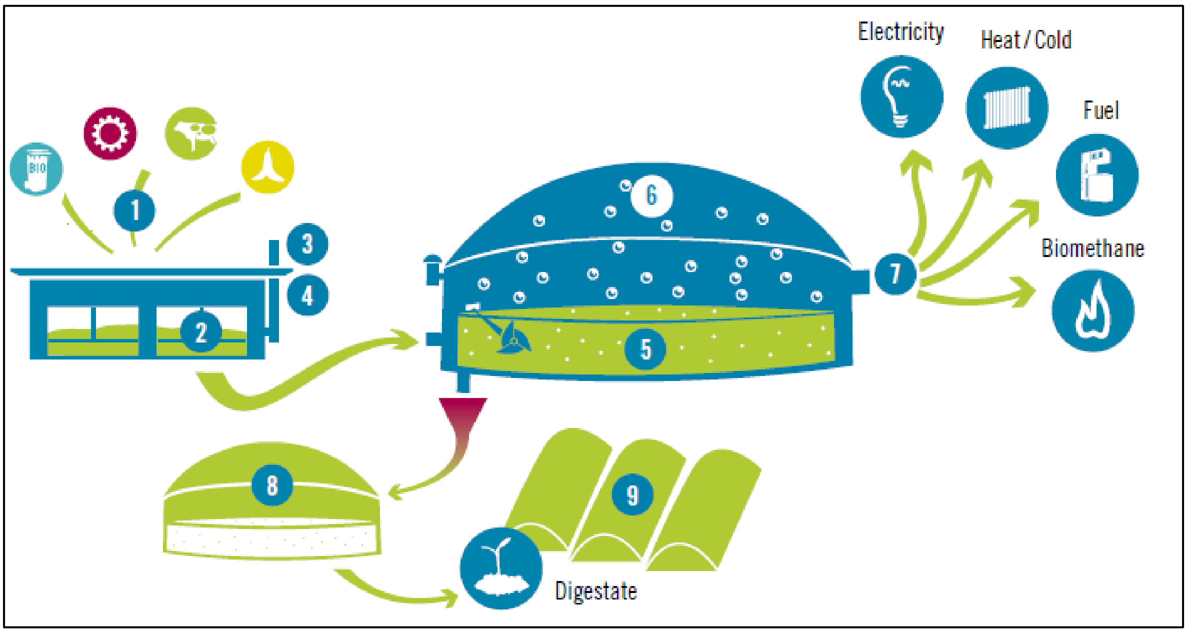

Figure 4: Scheme of a biogas plant 1: different types of feedstock, 2 storage of feedstock, 3+4: air collection and treatment, 5: digester, 6: biogas storage, 7: biogas application, 8+9: digestate storage; © FVB, 2009.

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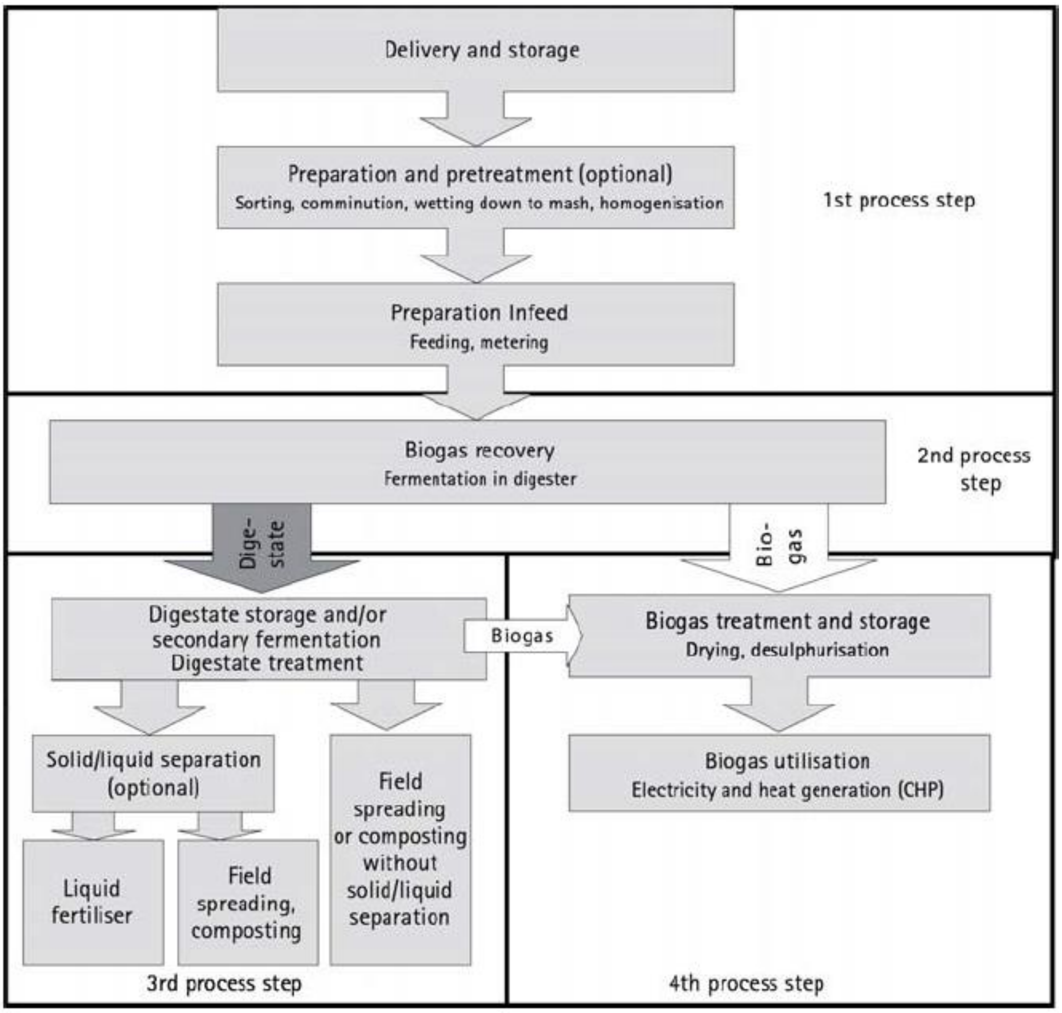

Figure 5: Usual process step of biogas plants; © Paterson, 2012.

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2 Receipt, storage, pre-treatment and handling of feedstock

Each biological process depends highly on ambient conditions but also on the feedstock being used. Therefore, it is very important to quantify and qualify the feedstock. In case feedstock is organic waste from households, catering etc., a pre-check on possible impurities is required in order to ensure that no substances will enter the digestion process that might inhibit the process. Depending on the source of feedstock the following steps are common:

- 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 entrance of typical biogas plants. In order to determine the amount and quality of the feedstock the delivered charge is weighed and a sample to determine dry matter content and volatile organic solids is taken. In some cases, also the nutrient content will be determined. This data will be recorded and further used for the steering of the digestion process. Some plants also take retaining samples and store them for further testing or, if problems occur, for a post-check on inhibitors. In general, substrates can be divided in two groups:

a) substrates which usually have no impurities and do not underly animal by-product regulation
b) substrates which may include impurities (e.g. pathogen bacteria (meat), heavy metals, plastic) and may underly animal by-product regulation (1069/2011/EU)

Agricultural residues -except for manure- belong mainly to group a) and usually accrue in huge amount during harvesting season. Therefore, different types of storage systems are needed:

- stacked in halls if dry, bulky and not putrescent (e.g. straw)
- stored in not gas-tight silos or halls if dry, not stackable and not putrescent
- stored in gas-tight silos if wet, bulky and putrescent/ likely to rot. The most common technique to avoid rotting during storage is to silage the feedstock in vertical or horizontal air-tight silos. Depending on the moisture content, the feedstock and the used storage technique, the preservation is done by CO_2 or by a reduction of the pH value.
- stored in tanks if liquid and not putrescent

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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.

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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.

Group b) of possible substrates that mainly underly additional animal by-product regulation, is usually delivered daily and, except for farm fertilizer, is possibly contaminated with different kind of impurities or even inhibitors. These substrates therefore underly completely different requirements after entering the biogas plant.

Feedstock from farms is usually delivered and fed directly into the digester. Only a very short storage time is foreseen for example for manure. Municipal organic waste is usually stored within waste bins before collected by special lorries on a weekly basis or even more often.

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Depending on the collection system, the waste bin will be directly cleaned after being emptied into the lorry by the collecting company or the waste bin will be transported to the biogas plant, emptied and cleaned there. Although many efforts are made to avoid food waste, sometimes food cannot be sold due to the exceeding expiration date. The best option then is to convert this organic waste streams into energy and use the digestate for nutrition. Companies from the biogas industry developed special devices to unpack and separate packing material or other impurities within one working step. If in Europe animal by-products are used as feedstock, sanitation requirements of animal by-product regulation need to be fulfilled (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Sanitation is usually done directly after acceptance and the substrate is usually pumped directly into the digester afterwards.

For substrate that might include impurities or needs to be crushed, a metal separation is done as a first step. Afterwards, different kinds of devices crush the substrate so that it can be treated more easily and to avoid damages.

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

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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.

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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.

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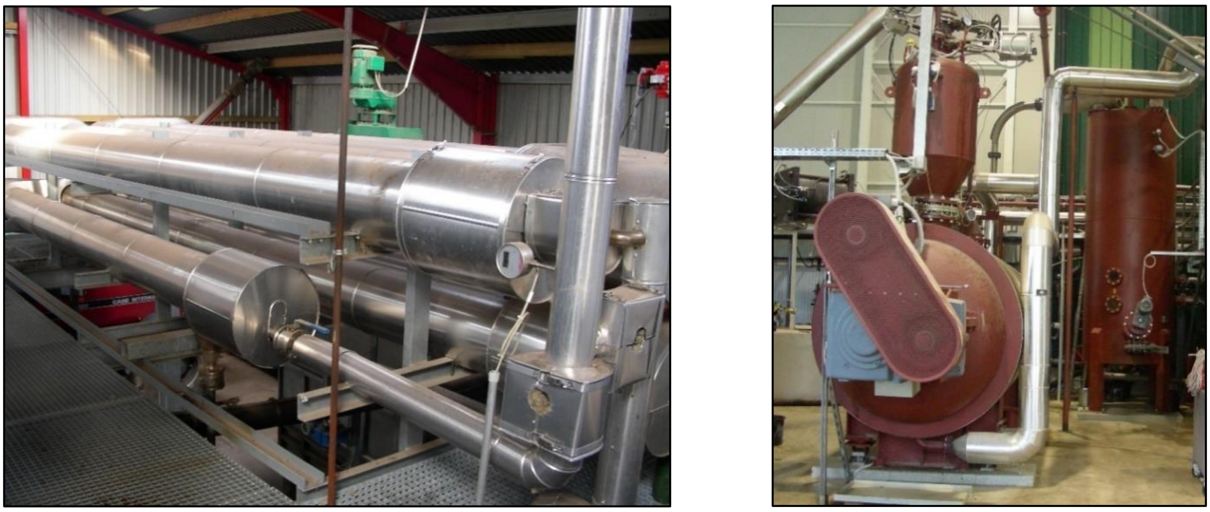
Picture 7: Left: unpacking machine for expired food with automatic separation of impurities, right: sanitation devices installed in parallel for higher performance.



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

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

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

Depending on the properties of the substrate and the digestion system, different systems are used for the transport of substrate within the biogas plant to the point of feeding into the digester. Most commonly used for the transport from the storage silo into the feeding system are wheel loaders, self-propelled distribution trailers, screw conveyors, conveyor belts and – if the substrate is liquid – also different kinds of pumps.

Picture 9: Self-propelled distribution loader.

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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.

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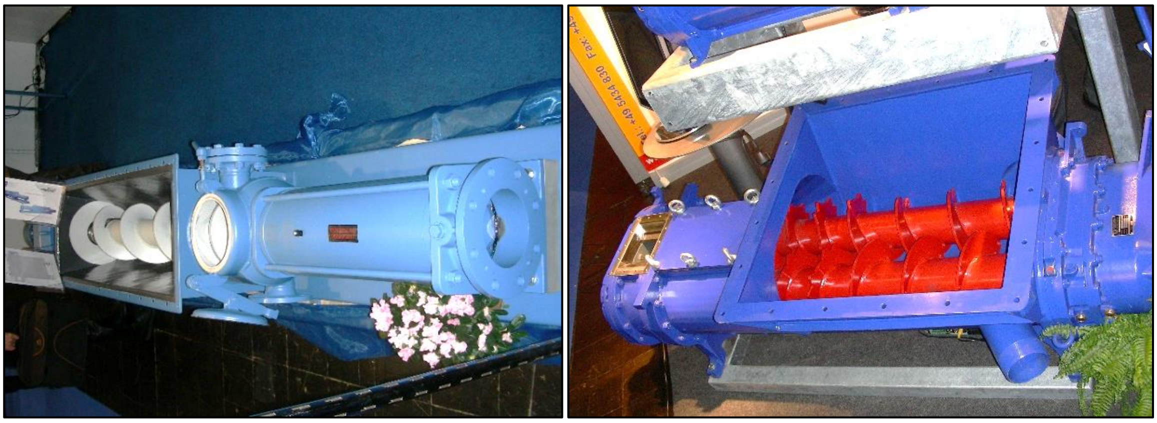
Picture 12: Substrate mixing tank followed by a feeding pump.



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.

The air of rooms where dangerous and often unpleasant odour can occur, must be ventilated, or collected and cleaned. This is usually done using a biofilter. The collected air is pressed from the bottom into 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 must be controlled.

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

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3 Digester

Although pre-treatment of used substrate is a very important step for the performance of anaerobic digestion, the digester can be seen as the main technical facility in a biogas plant. Corresponding to the biological, chemical and technical requirements, biogas plants can be classified as shown in table 9.

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

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

3.1 Wet or dry fermentation

There is a difference between wet and dry fermentation. Irrespective of this differentiation however, every biological process – and thus also the process of fermentation – requires the presence of water. Hence, the real difference lies in the form of the substrate: either it is liquid, solid or even stacked.

Inside the digester there has to be always enough water for bacteria to be active, even in dry fermentation. In consequence, there is no general definition for dry fermentation. In some countries, the water content of the feedstock is used as a differentiator: if the average dry matter content of the feedstock is above 25% (or above 20%), it is defined as dry fermentation.

In other cases, it is called dry fermentation if the feedstock inside the digester is stackable, for example in cases of dry batch garage systems.

3.2 The substrate feed: Continuously vs. intermittent feeding systems

Most biogas plants are fed continuously, which means several times per day. Thereby, relatively constant conditions in the digester tank can be achieved which is beneficial for the

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activity of the microorganisms. However, the substrate can also be fed into the digester intermittently, only once a day. Yet, this is seldom the case as this would hinder a continuous biogas production and could additionally cause process distortions. Some special liquids are fed into the digester continuously. The same volume which is fed into the digester will be forwarded to the next fermentation step, e.g. into the post digester or storage tank. This can be done via steered pumps or through free flow. The filling level of the digester itself therefore is kept at the same level and guarantees a continuous biogas production. Even less frequently used are garage type digesters, where stackable feedstock is only fed in batches, e.g. once per month.

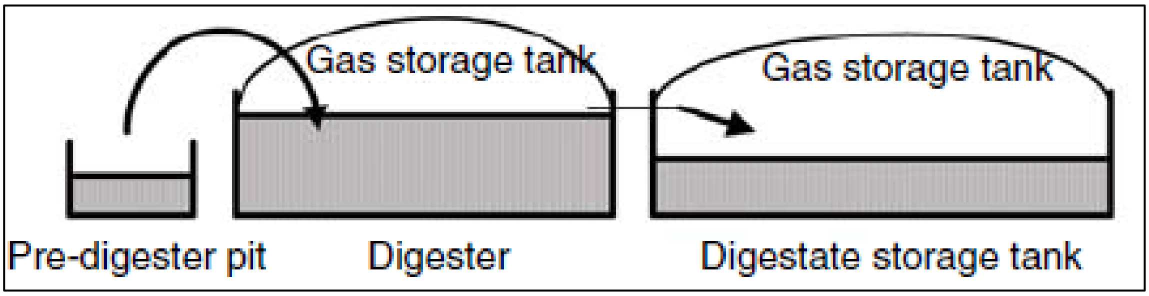

Figure 6: Continuous digestion process called through flow process with a followed gas-tight storage tank; ©FNR,2012.

3.3 The hydraulic flow: continuously stirred, plug flow digestion, or batch digester

Most wet digestion systems are continuously stirred (**CSTR: continuously stirred tank reactor**). In these systems, one or more agitators secure that the substrate within the digester is in continuous flow so no segregation into floating or sink layer occurs. Additionally, it shall guarantee that no zones occur where the temperature gets too low or where the acid concentration etc. raises too much. The stirring can be done continuously or semi-continuously. In case of the latter, stirring needs to be done at least before floating layer etc. occur.

A special form of continuously stirred digesters is the **hydraulic digester** where the stirring is done with the gas pressure of created biogas. It is usually a tank in tank digester 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 within the connection gas pipe is closed, the produced biogas presses the substrate in the outer tank, flows through the opening at the bottom into the inner tank and raises the level of substrate there. After a difference in height between the liquid surface of inner tank to outer tank of around 4 meters, the valve is opened, and the fluid levels are immediately equalized through the concentric bottom openings. These concentric openings guarantee the stirring of the substrate.

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 vertical installed plug flow digesters in operation. Both, horizontal or vertical systems can be operated in dry or wet fermentation processes. The different steps of digestion are separated in this type of reactor. Which is an advantage as the different bacteria groups can all work within their own optimum pH range.

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The vertical plug flow system is called UASB digestion (**UASB = up flow anaerobic sludge digester**). This is a special type of digester which is often installed to reduce chemical oxygen demand in wastewater from industries like dairies, beverage industries, sugar beet factories etc. It treats fast degradable liquid substrates with a retention time which is sometimes only around one day. As methanogenetic bacteria has a doubling time for at least 2 days, this would cause washing out of the last step of biological digestion process from the digester and therefore lead to process disturbances. Therefore, special conditioned pellets are filled into the digester where the methanogenetic bacteria can settle while the liquid substrate streams upwards and passes the bacteria. The substrate at the bottom is pumped continuously into the digester and flows slowly upwards. At the top of the digester the generated biogas is collected in special domes.

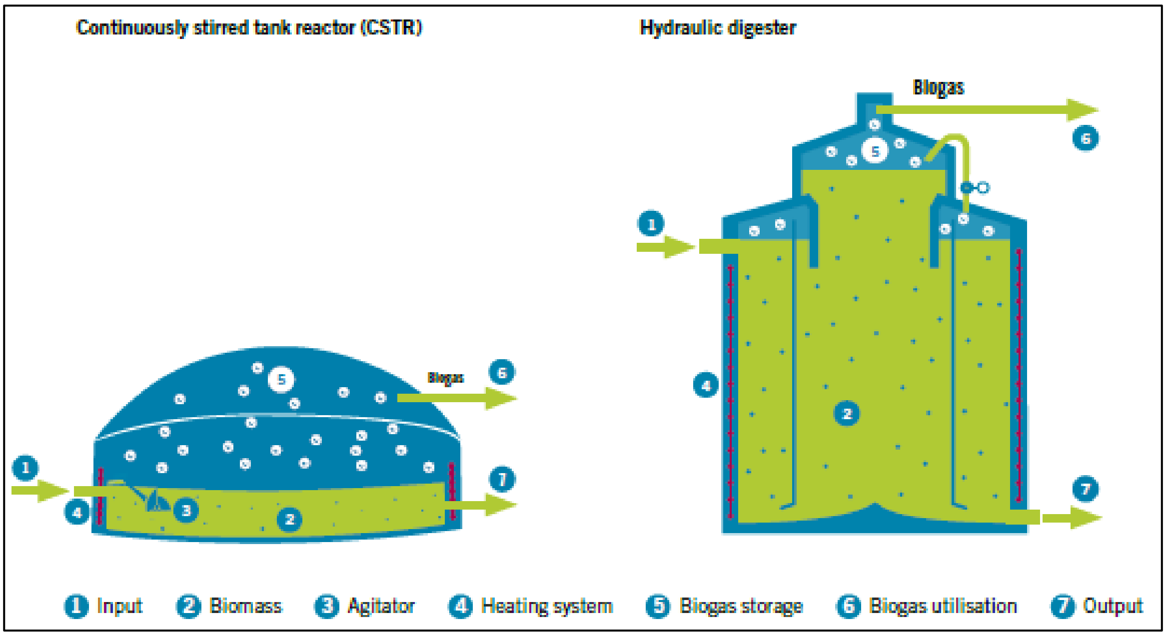
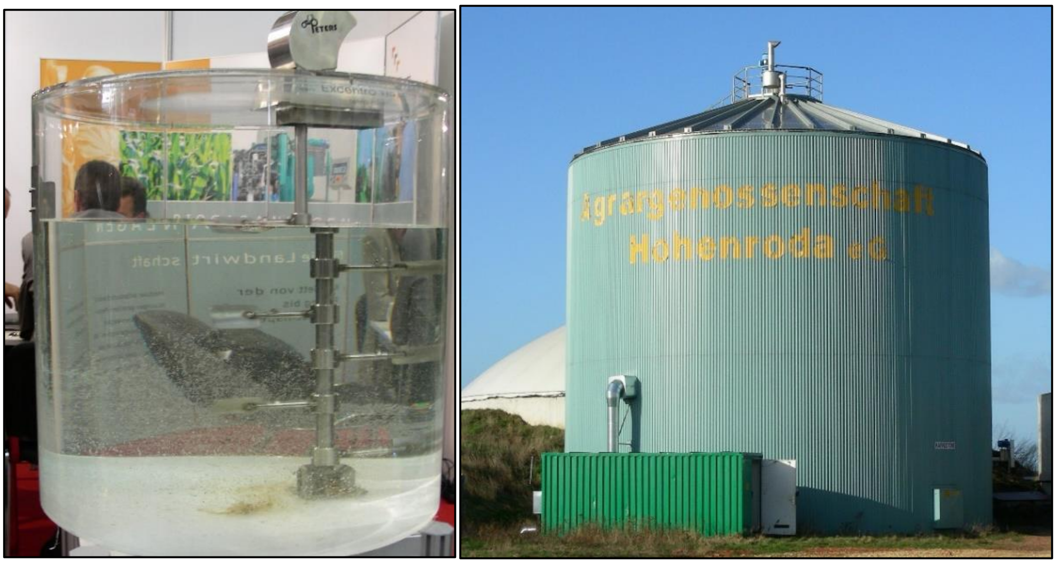


Figure 7: Types of continuously stirred digesters; left: stirred by agitator, right: hydraulically stirred; © FvB, 2017.



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

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

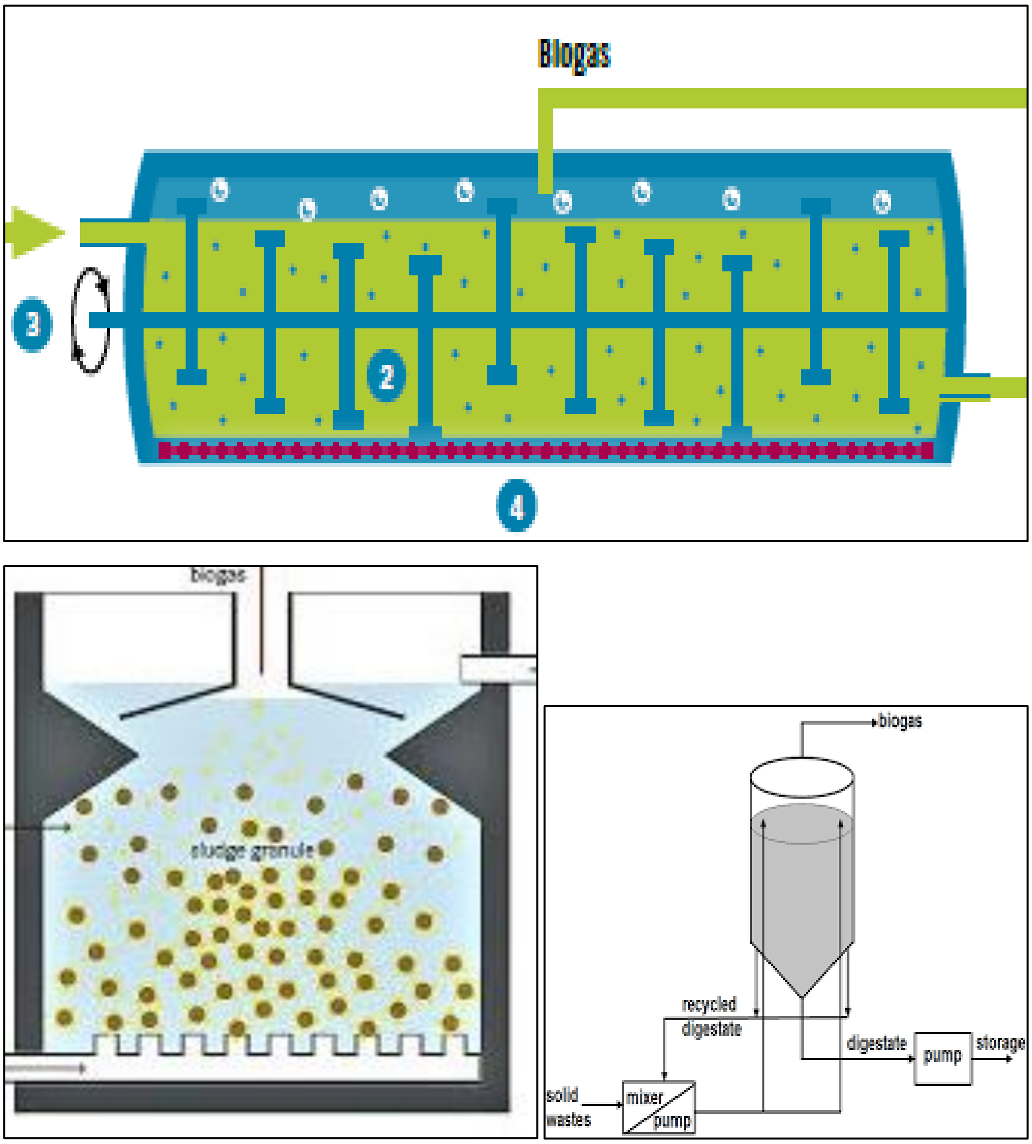

Figure 8: Schemes of horizontal and vertical plug flow digester; top: horizontal plug flow digester with horizontal agitator, bottom left: vertical downstream plug flow dry digester without mixing, bottom right: vertical upstream plug flow digester without stirring.

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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).

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

Another special form is the batch dry digester (also called **garage system**). Here the substrate is filled in a closed room (garage) which is air-tight closed after filling the feedstock. The substrate needs to be stackable and will not be mechanically mixed during the subsequent digestion process. During this digestion process percolate (intercellular water which will be set free from the feedstock during the digestion process) will be pumped and spread from the ceiling onto the substrate. The acid-rich percolate is collected at the bottom and pumped to the heated percolate tank. The biogas process usually happens within the stacked substrate and also within the percolate tank. Through the flow rate etc. it can be steered where most of the methanogenic process happens. When the substrate is degraded, the digester is aerated and afterwards emptied and filled again with new substrate. As the building of biogas is not continuous with one batch, these systems usually have several batch digesters installed in parallel.

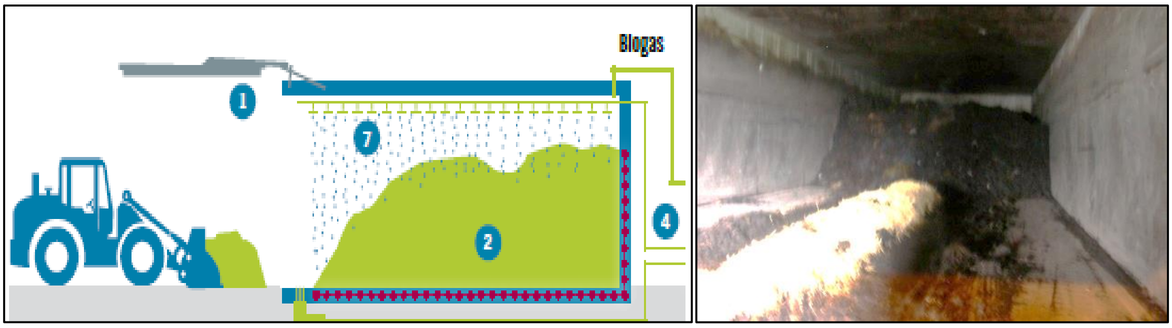

Figure 9: Top: Scheme of a batch dry digester bottom: inside of a batch dry digester; © left Fachverband Biogas 2019.

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3.4 Biological process phases: single or two phases

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 stages: single, two or even multi-stage

Many biogas plants are designed as follows: a main digester, followed by a post digester, followed by a gas-tight storage tank. This is the case because in a continuously or semi-continuously stirred digester not fully degraded substrate leaves the digester and thus, maximum biogas yield cannot be achieved. To ensure an environmentally friendly performance, formed methane from the digestate storage tank should be collected and used. As the feeding is done into the main digester, the size and maximum loading rate of this main digester determine the total capacity of the plant. Therefore, the organic loading rate in the main digester is higher than in the post-digester. If substrate is used that might cause a process distortion, these arrangements can help to avoid such a process distortion. In case the process

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is disturbed in the main digester, due to an excessive loading rate, this can be solved with substrate from the post-digester. However, it is important that the main and post-digester have nearly the same temperature as otherwise the difference in temperature could make the situation even worse. In contrast to the biological two-stage digestion process, the whole biological degradation process occurs simultaneously in each digester.

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: psychrophile, mesophilic or thermophilic process

The biogas process can operate within different temperature ranges:

- psychrophilic (<25°C), not very relevant in practice
- mesophilic (35 - 38°C), most common temperature
- thermophilic (>50°C), fastest degradation

The higher the temperature, the faster the growth rate of the microorganisms. The most commonly applied digestion temperature is the mesophilic profile. Mesophilic operation offers high process stability and a good controllable process. The thermophilic process on the other hand, is more sensitive to process disorders (especially to a higher amount of nitrogen within the substrate) and to temperature fluctuations. In a proper operated thermophilic process, the digestion process is performed faster, and the bacteria can adapt slowly to a higher ammonia content. Faster growth and activity of microorganisms mean faster digestion. Consequently, required retention times are lower, the digester can be smaller and can be operated with a higher loading rate and still reaches the same biogas production. In many emerging and

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developing countries biogas plants are operated at ambient temperature, e.g. lagoon and little domestic biogas plants. The advantage is that no heating system must be installed. The disadvantage is a lower activity of the microorganisms and probably lower biogas yields. Additionally, high digester volumes must be built because at low activity of bacteria, high hydraulic retention times are needed.

Industrial biogas plants usually optimize their operation. To reduce needed investment, operational and possible maintenance costs, the digester volumes should be small. They have a heat recovering system with the CHP unit and therefore prefer mesophilic operation.

3.7 Material and insulation of digester

Common digester material is locally produced concrete, steel, enamel- or even stainless steel. Common steel can be used for digesters if the desulphurization via oxygen is not made in the digester itself as this would lead to corrosion. This means, that biogas from these digesters always contains H_2S which needs to be taken into consideration for all further equipment. In case that locally produced concrete is chosen, the quality of the concrete and of the used cement is very important. In order to ensure longevity of the installation, the concrete placement must be combined with the right post-treatment. For an optimal process efficiency, the digesters need to be fully isolated (floor included) so that every zone of the digester has the same temperature. A fluctuation of 1 °C within a day already causes negative effects on the performance of the bacteria.

Picture 22: Concrete digester.

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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 avoid segregation of the substrate in the digester, digesters – except the ones where it is not wanted or done in a different way – need to be stirred by an agitator. Vertical tanks are

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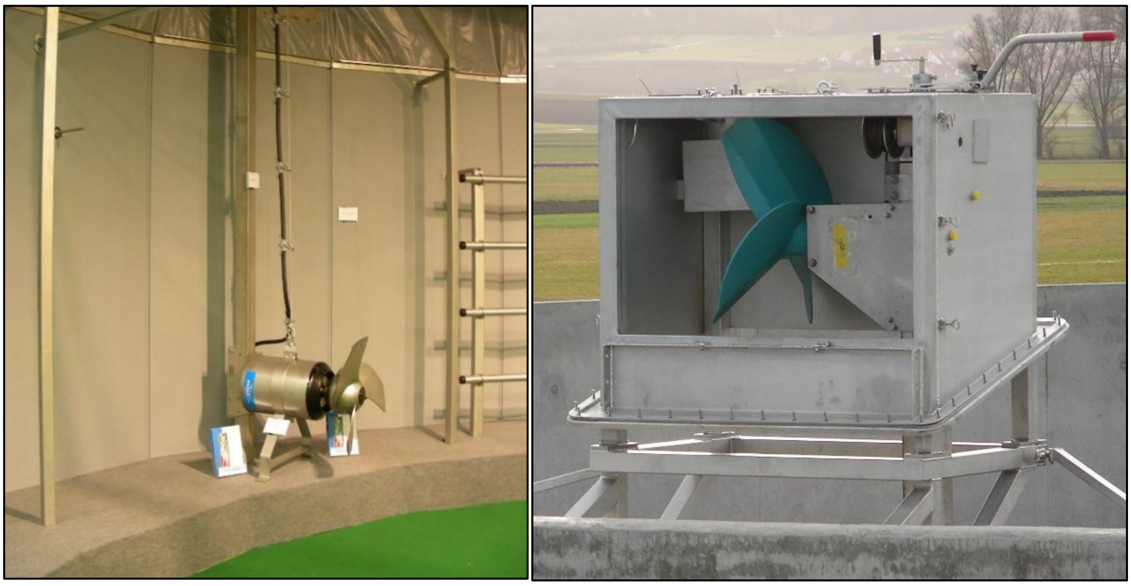
often stirred continuously by a central disposed agitator. Other commonly used techniques are propeller agitators (fast or slow running) or paddle agitators.

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



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

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Picture 27: Different types of slow speed agitators.

Picture 28: Slow speed agitator in a horizontal digester.

3.9 Heating

Several microorganisms are sensitive to temperature changes. Therefore, digesters need to be insulated and heated to keep a constant temperature with variations less than 1 °C per day. Heating is usually done through stainless steel pipes or plastic hoses which are directly installed at the inside of the walls and thus are directly in contact with the substrate.

When steel digesters are used, the pipes for heating are sometimes also installed between the steel and the insulation. For concrete digesters the heating pipes can also be directly included

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within the concrete wall. Furthermore, also external heaters are used. Here, 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.

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4 Pumps, Pipes, Valves

In a biogas production unit, pumps, pipes, and valves are necessary to transport liquid substances. This mostly concerns liquid substrates, digestate and to a lesser extend also liquid additives. The liquid substrates need to be pumped to the mixing tank and consequently to the digester. After digestion, the digestate is most often pumped to a digestate storage tank.

This chapter will first discuss different types of pumps in biogas systems. Next, the requirements for pipes and valves for liquids are described, together with some examples. Lastly, different often applied security and control equipment for pumps, pipes and valves are introduced.

4.1 Pump types

Physical properties of substrate types for biogas production can largely differ. The dry matter content, particle size, temperature, the viscosity, and possible impurities in the substrate can for example vary. To handle the large range of different liquid substrates used for biogas production in addition to handling all stages of fermentation, different types of pumps are available. Nevertheless, preliminary removal of stones and other impurities can be necessary to facilitate pumping. Additionally, concentrated substrates can be diluted to allow for smooth pumping. Below, four different types of pumps often used at biogas facilities are discussed: rotary pumps, rotary displacement pumps, cavity pumps and peristaltic pumps. In practice, the pumps used in biogas applications are often of a similar kind as the ones used for liquid manure pumping.

Despite precautionary measures and good substrate pretreatment, pumps can clog and need speedy clearing and regularly maintenance. Therefore, it is recommended to make pumps readily accessible with sufficient working space kept clear all-round. 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, transport of liquids within the biogas plant is handled in its entirety by one or two pumps centrally sited in a pump station or control cabin. The piping is routed in such a way that all operating situations are controlled by means of readily accessible or automatic valves.

Pumps can be divided into self-priming pumps and pumps which are not self-priming. A self-priming pump is capable of freeing itself from air entrained in the pump and start normal pumping. This property makes the pump suitable for being placed above the liquid level using a suction pipe. Contrary pumps which are not self-priming pumps must be situated below the liquid level. From the pumps described below, rotary pumps are not self-priming, while the different types of positive displacements pumps (rotary displacement pumps, cavity pumps and peristaltic pumps) are self-priming.

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4.1.1 Rotary pumps

Rotary pumps are commonplace in liquid-manure pumping and eminently suitable for runny substrates (dry matter content below 8%). A rotary pump has 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 this fixed amount of liquid is trapped, the volume is constant through each cycle of operation 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 interfering substances, thus it is recommended to have good pretreatment and removal of impurities before pumping of the

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substrate. The often-applied 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 body. 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.

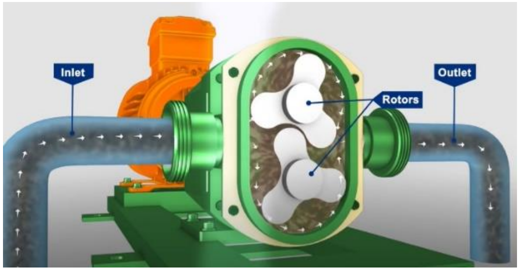

Figure 10: Rotary displacement pump.

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. Depending on 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 or volume does 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 suctioned and develops a volumetric flow directly proportional to its rotation. Figure 11 shows the working principle of a progressive cavity pump. For cavity pumps, it is especially important to foresee enough space in front of the pump for pulling out the rotor in case maintenance is required.

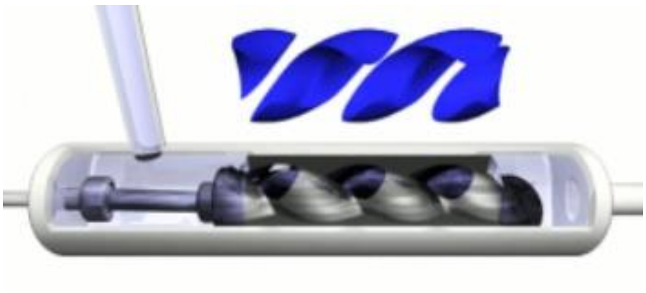

Figure 11: Cavity pump.

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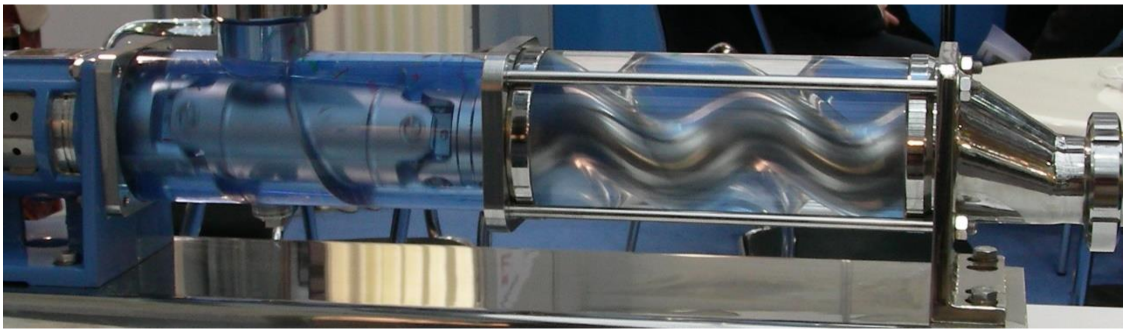

Picture 35: Cavity pump.

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 is attached in such manner that the lobes compress the flexible tube. As the rotor turns, the lobes force the fluid to be moved through the tube, which can be compared by squeezing toothpaste out of a toothpaste tube. It is the same principle, which allows fish being pumped without begin squashed. The working principle of a peristaltic pump is shown in Figure 12.

Picture 36: Peristaltic pump.

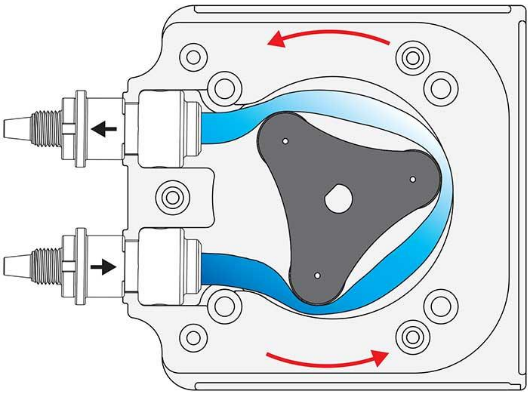

Figure 12: Peristaltic pump.

4.2 Pipes and valves for liquids

Pipes and valves discussed in this subchapter concern pipes and valves used for transporting liquids in the biogas plant. Valves prevent unwanted flows of liquids e.g. from the digester to the pre-digester pit or between digesters. Due to safety requirements, sometimes, double valves are installed so if the main valve would cause a leakage, the second valve can be closed.

Pipe materials often used are PVC, HDPE, steel or special steel, depending on the medium, temperature and pressure level. Most valves are made of stainless steel.

Some important requirements for pipes and valves for liquids are listed below.

- Piping, valves, and fittings must be medium-proof, temperature proof and corrosion-resistant.
- Valves and fittings must be readily accessible and operable
- They must be installed in such a way to be safe from frost damage.
- Suitable insulation has to be fitted for handling warm liquids.

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- All materials must be chemically resistant to the liquid and must be rated for maximum pump pressure under a given temperature.
- Piping must be routed to prevent backflow of liquid e.g. from the digester to the pre-digester pit.
- Cast iron piping is considered not a good choice, because the formation of deposits is more of consideration than in smooth-surfaced plastic pipes, for example.
- Pipes below surface should have a leakage monitoring

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 along the pipe and hardly restrict the flow of fluid when the gate is fully opened. Gate valves are installed e.g. upstream of each flap trap. 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 in case interfering substances prevent the flap trap from closing correctly. Gate valves can additionally be installed as shut-off valves allowing pumps to be isolated from the piping system.

- **Manually vs. automatic valves**

While manual valves are actuated by a qualified person, automatic valves can be remotely controlled by an automated computerized control system. Automatic valves have additional control devices installed which check the actual position of the valve, to make sure the automatically steered valves are at the correct intended position. Both types of valves are considerable different 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. Using a time clock, a computer will turn the pump on and off at predetermined times. Alternatively, or in addition a control system can be installed. The control system usually consists of pressure sensors and/or flow rate measuring. These sensors will monitor the pressure and flow rate

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before and after the installed pump and compare those values with the desired computer value. The control system can adjust the pump speed in order to reach the desired condition. Using a control system, the process can be either fully or partially automated. Apart from controlling pump speed, pressure sensors before and after the pump are installed to check for vacuum (before pump) or too high pressure (after pump) to detect maloperation and thus avoid damage to pumps, pipes, and valves.

Often, the current demand for pumping is recorded and shown on a graph. A significantly higher current demand may be due to worn pumping parts such as the rotor or stator from a cavity pump. Possible other reasons for high current demand are higher viscosity of the pumped liquid, oversized impeller installed in a rotary pump, rotating parts in contact with stationary parts etc.

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5 Gas compression devices, pipes, valves

5.1 Introduction

In a biogas production unit, gas compression devices, pipes, and valves are primarily necessary to transport the biogas produced. Additionally, they are also required for double membrane gas storage systems and for oxygen supply in case desulfurization of the biogas is done via oxygen injection (further information in chapter 10). The piping systems connects all digesters in which the biogas is produced with the biogas appliances such as the CHP unit or the biogas upgrading unit and also to the biogas storage system.

This chapter discusses two types of gas compression devices, one for biogas compression to transport the biogas to the utilization device and one used in double membrane gas storage systems. Next, the main requirements for pipes and valves for gases are introduced.

5.2 Types of gas compression devices

Depending on the needed flow and pressure, usually the following types of gas compression devices are 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 gasflow. The fan has the shape of a drum with a ducted output. Inside the drum a propeller accelerates the gasflow and the ducted housing directs 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 a similar 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 often-applied positive displacement compressors at biogas facilities are piston compressors and screw compressors.

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5.2.3 Piston compressor

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

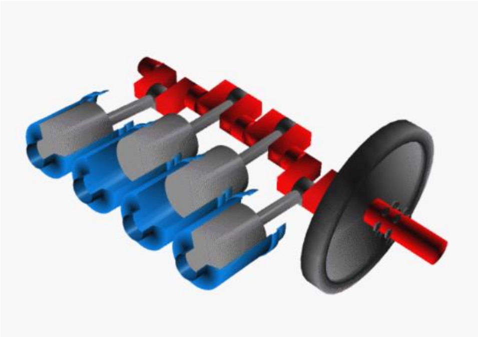

Figure 13: Illustration of the working principle of a piston compression.

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

5.2.4 Screw compressor

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

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5.3 Application of gas compression devices

5.3.1 Biogas compression

Biogas is not typically produced at equal quantities and equal quality over time and in the exact amounts required by the utilization device (CHP, upgrading unit or other devices). Therefore, gas storage systems are used to smooth out variations.

To subsequently transport the biogas from the biogas storage to the utilization appliance, gas compression devices are used in a similar way pumps are used to transport liquids. The compression device can both “pull” the biogas from the storage and “push” the biogas towards the utilization appliance. The biogas will be delivered at constant pressure to the gas utilization unit.

The operating gas pressure in most anaerobic digesters is low (only some mbar) while the gas utilisation unit is usually constructed to operate with higher pressure. In addition, transport of biogas through piping entails pressure loss. Compression devices for biogas are thus needed to bring the biogas at a higher and suitable pressure required by the gas utilization unit.

5.3.2 Double membrane gas storage

For temporary buffering due to fluctuations in gas production, storage of produced biogas is required. Biogas can be stored either 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. Thus, in this case the gas compression device is not transporting biogas, but instead is blowing air to enable safe biogas storage.

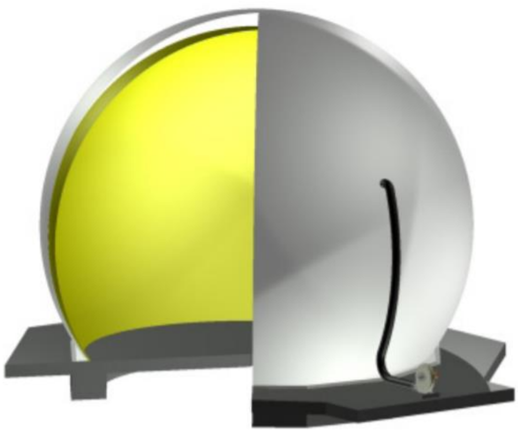

Figure 14: Double membrane gas holder

Usually, the volume of the gas storage is dimensioned according to the gas usage. If the gas is utilized 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 unit is based on flexible operation (e.g. a CHP operation depending on the demand of the electricity grid) the gas storage might be bigger, e.g. holding about 8-12 h biogas production. In nearly all cases the gas storage system is dimensioned to balance demand and consumption on a daily basis and not to balance seasonal variations.

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5.4 Pipes and valves for gases

Pipes and valves discussed in this subchapter refer to pipes and valves used for transporting gases (biogas and biomethane) throughout the biogas plant. Galvanizes steel (G.I.) or Polyvinyl chloride (PVC) are 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 vapor. It contains hydrogen-sulfide and other corrosive components. Consequently, no piping and valves that contain any amounts of ferrous metal may be used for biogas piping, because they would corrode within a short time.
- The piping systems needs to be safe, economic and should allow the required gas-flow for the specific gas appliance.
- The piping systems needs to be reliably gas-tight during the lifespan of the biogas unit. In the past, faulty piping systems were the most frequent reason for gas losses in biogas units.
- All parts of the piping system above ground must be resistant to environmental damage such as UV, heat, and fracture. For this reason, galvanizes steel pipes are suitable above ground whereas PVC pipes are not recommended and often not allowed above ground.
- When placing pipes underground, the subbase must be well compacted before pipework is installed. The entire pipework should be free of stresses and strains. If necessary, bellows adaptors or U-bends should be included.
- When the piping is installed, it has to be tested for possible gas leakage.
- All valves, fittings and pipes must be suitably protected against frost.
- As the biogas is saturated with water, there will be condensation if it cools down in the pipes. Therefore, pipes must run with enough fall (1-2%) to ensure that condensate, slight settling, or sag cannot produce unintended high points along the runs. Considering the low pressures in the system, small quantities of condensate can suffice to cause a complete blockage. The piping system must be equipped with condensate traps in which water can be extracted from the system.
- All valves must be readily accessible, easily serviced and easily worked by an operator.

Examples

To the extent possible ball valves or cock valves suitable for gas installations should be used as shut off and isolating elements. With shut off valves, cleaning and maintenance work can be carried out without closing the main gas valve. The most reliable valves are chrome-plated ball valves. Gate valves of the type normally used for liquid transports are not suitable.

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- **Ball valves**

A ball valve consists of a valve body with 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, and when turned one-quarter of the way, the flow stops. The port of a full port or full-bore ball valve equals the pipeline diameter and presents little or no restriction to flow. The port of reduced port or reduced bore ball valve is smaller than the pipe and absorbs a small amount of pressure drop.

Figure 15: Ball valve

- **Cock valves**

Cock valves have a similar working principle compared to ball valves. Instead of a ball, a tapered plug with a through-port is in place. By turning the plug one-quarter, the through-port will either be parallel or perpendicular to the flow, allowing or stopping flow through the valve.

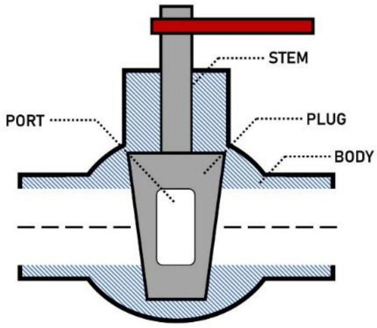

Figure 16: Cock valve

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6 Safety Equipment

The production of biogas is a complex engineering process which involves the manipulation of highly flammable gases and other hazards. However, if the adequate safety measures are taken reducing all potential risks, the biogas plant can be operated safely. It is important to consider safety measures already at the planning phase and during the whole process of biogas production. In this chapter, we will describe the main hazards present in a biogas plant and the basic equipment that any biogas plant requires to be operated safely.

6.1 Overview on environmental and health risks in a biogas plant

Before we analyse the safety equipment needed in a biogas plant, it is important to understand the main potential risks of the biogas production process. Biogas is produced by the breakdown of organic matter by bacteria that metabolize the organics releasing different gases. This process is called anaerobic digestion (AD). The main components of biogas obtained vary widely depending on the feedstock used and the digestion temperature. The main components of biogas are methane (range of 50 – 75 %) and carbon dioxide (range of 25 – 50 %). It also contains impurities, such as hydrogen sulphide, ammonia and other gases.

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

In addition, some of the gases present in the biogas production process entail **health risks for humans**, including damage for potential explosions, suffocation and exposure to poisonous gas hazards.

Typical health risks for humans are

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

The 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.

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

	Biogas (60 % CH_4)	Natural gas	Propane	Methane	Hydrogen
Heating value (kWh/m³)	6	10	26	10	3
Density (kg/m³)	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 (m³/m³)	5.7	9.5	23.9	9.5	2.4

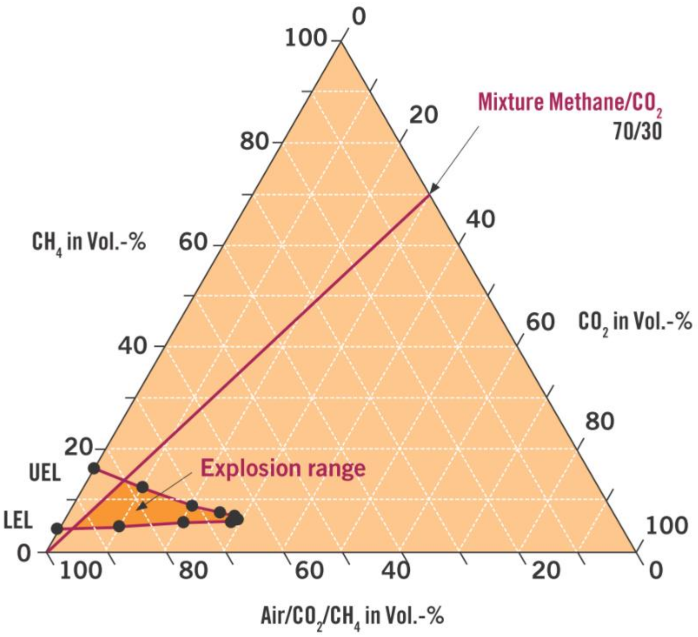

Figure 17: Explosion triangle for biogas. Source: UEL: Upper Explosive limit, LEL: Lower Explosive Level, German Biogas Association/GIZ

It is important to constantly monitor the concentration of the different gases present in biogas facilities. The table 11 below collects the properties of the main gases present in biogas facilities and the main health and environmental hazards these entail:

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

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.

Other risks entail the manipulation of mechanical and electrical equipment of the biogas plant. In that case, correct training for operators and adequate maintenance procedures are key to avoid any hazardous operation of the equipment.

The infographic below shows the different hazards we can find in a biogas plant, classified in 5 different categories:

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

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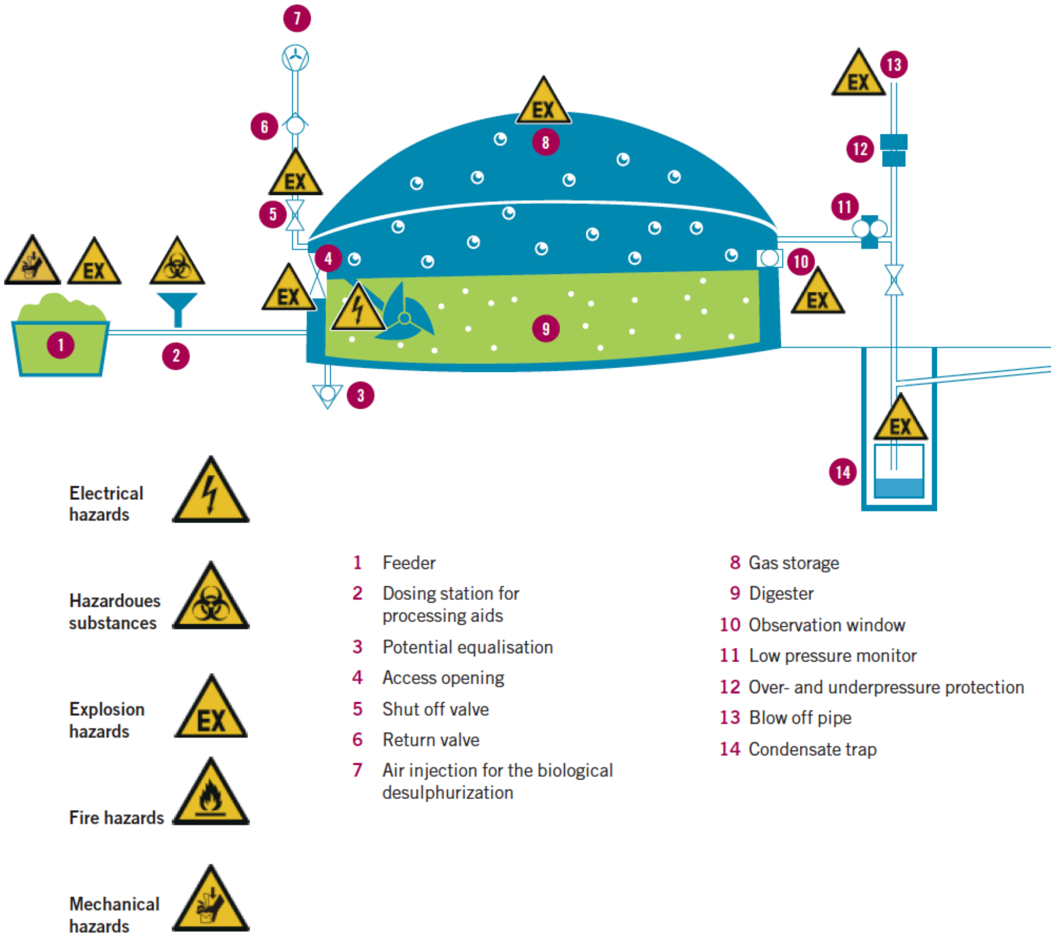

Figure 18: Hazards we can find in a biogas plant. Source: German Biogas Association (FvB)

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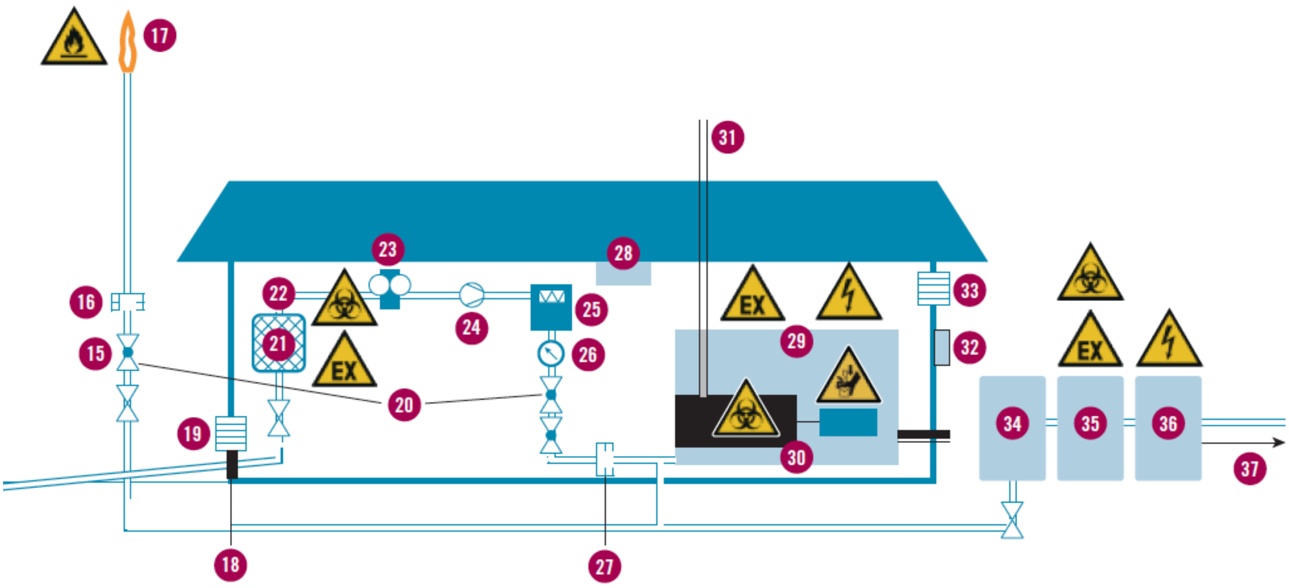

15 Shut off valve
16 Flame arrester
17 Gas flare
18 Fire protection for the wall entry of the gas pipe
19 Fresh air inlet
20 Autmoatic shut-off device
21/22 Gas fine filter/Activated carbon filter
23 Low pressure monitor
24 Compressor
25 Gas-counter
26 Manometer
27 Flame arrester
28 Gas warning device
29 CHP (Combined Heat and Power Unit)
30 Oil tray
31 Exhaust pipe CHP
32 Emergency switch
33 Air outlet
34 Upgrading unit
35 Conditioning unit
36 Injection unit
37 Utilization of biomethane

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

6.2 Safety equipment

Safety equipment shall help avoiding damage of the installations and 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, personal protective equipment.

6.2.1 Installed devices

Installed devices shall prevent over or under pressure within the airtight systems of the biogas plant. If excessive pressure is detected in the airtight gas system, a flare will burn the excess

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of biogas to prevent an explosion and prevent methane emissions into the air[1]. Gas warning systems will signal spaces with gas concentration risk.

Control system

The optimization 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 absence of oxygen and at a usual temperature between 38° C and 55° C.

The process is affected by external parameters, such as local weather conditions, environmental changes and changes in daily feed load. It is therefore critical to monitor the AD process as closely as possible. This will facilitate the detection of unstable process states. We always should have in mind that the main "work" in the digester is done by microorganisms. The living conditions for those living species must be as optimized as possible but they might change within the AD process (due to feedstock, temperature variations, pH values etc.). Close monitoring and steering of the parameter are essential for optimal biogas plant operation.

Plant operators can use predictive models that will help them stabilize the fermentation that takes place in the digester during the AD process and have higher control on the biogas output that will be obtained.

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

Occurring under pressure:
If the quantity of substrate removed is liable to exceed the volume of gas generated, the pressure in the tank will drop down and a damage of the system might occur. If this happens, the digestion tank is shut off from the gas collection system. Afterwards, the under-pressure protection device would be triggered, and an alarm signal would warn about under-pressure in the tank.

Occurring over pressure:
If the production of biogas is higher than the use of biogas and the storage capacity is limited, this could result in a raise of pressure. That might lead to damages in the system. To lower the biogas production, the feed of feedstock might be reduced which would lead to lower biogas production within several hours. This shall happen already before the gas storage system reaches 100 % full capacity. However, if overpressure is present in the gas system a gas-consuming facility (e.g. gas flare, boiler, CHP) should prevent the uncontrolled release of biogas. If there is still over pressure the over pressure valve will open and make sure that no damage will happen to the biogas plant. In that case, biogas would be released into the atmosphere without previous treatment. This should only be the last step in the safety chain.

Chronological order avoiding over pressure:

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

[1] Methane has a very high GHG potential.

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Over and under pressure devices

It is important to monitor over and under pressure in the airtight tanks where biogas is contained. The over and under pressure valve is an essential safety component of a biogas plant. The valve is designed to avoid that the gas contained in the airtight tank raises above or falls below set limits.

In the event of over pressure, the exceeding amount of gas will have to be released and safely discharged. If there is a significant drop of pressure, the system must safely compensate the drop by allowing outside air to flow in until pressure reached safe levels again.

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 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).

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Flare

Biogas flares are used to safely burn biogas that is surplus to the demand of the energy recovery plant or where the recovery plant fails. The gas flare system must meet the general requirements for plant components exposed to gas. It must be leak-tight, 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.

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

- open flares
- enclosed flares

Picture 43: Enclosed flare in biogas plant.

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 different meters above the ground to protect workers and supply pipework.

Enclosed flares are usually ground based. The burner is protected by a cylindrical enclosure of refractory material. As the enclosure isolates the flame, the control over the combustion process is higher and emissions are lower. These flares include control equipment allowing to flare gases with different compositions and flows. Enclosed flares burn at a higher temperature and are design to keep the gas burning inside the chimney for a specific amount of time (residence time) to ensure complete destruction of any toxic elements contained within the biogas.

Gas warning systems

Constant monitoring of the work environment is key to ensure the early detection of gas in hazardous areas. This can prevent damages or contain existing ones. Fast and reliable detection of leakages is ensured by placing fixed gas warning systems in the proximity of possible gas release sources.

These devices are used to measure hazardous concentration of 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, and oxygen depletion. Even the smallest gas leak will trigger an alarm to prevent operators working in the area. Operating instructions must be written in the case of the alarm being triggered by the gas-warning device or in the event of interruptions of the gas-warning device.

It is important to carefully assess the best placement for these devices before their installation considering all elements that could interfere with an accurate reading on the sensor, such as

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gas weight or air flow. In addition, gas warning systems must be appropriately calibrated, wired and maintained.

Fix installed devices are connected to the control unit and will give an alarm if the lower explosive level (LEL) is reached. Additionally, ventilation of this room would start operating at full load. If the upper explosive limit (UEL) is reached, the control unit will shut the gas biogas outside of the room, all electric devices in the room will be shut down and current will be disconnected. Entering the room would be only allowed to special equipped teams.

6.2.2 Portable devices

Gas detectors

Explosion, suffocation, and poisonous gas hazards may be detected using portable gas devices. These detectors are used as personal equipment and carried by the staff to evaluate the potential presence flammable or toxic concentrations of methane, carbon dioxide or hydrogen sulfide 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 specialized 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 odorless and high concentration of hydrogen sulfide can immediately neutralize 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 to 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 preventive measure, plant operators must not enter a facility where there might 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 dangerous atmosphere is detected, the area has to be departed immediately and safety instructions written down in the operation manual have to be followed. Operating instructions must be written in the case of the alarm being triggered by the gas-warning device or in the event of interruptions of the gas-warning device. Additionally, such cases have to be reported into the operating logbook.

Personal protective equipment

When recommended by safety instructions, personnel working in a biogas plant must wear a protective equipment ensuring protection to avoid direct exposure to toxic and flammable gases. If the staff enters a zone with hazardous concentration of gases, they will need to wear a gas detection device and measure gas concentrations before entering that zone. When

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entering without a gas detection device, they must wear adequate clothing and use non-sparking equipment.

In addition, it is important to observe specific cleaning routines. These include washing hands before going for breaks and upon completion of work, as well as regular cleaning and ventilation of the workplace, 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 within the whole area of the biogas plant. 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.

The figure 20 below illustrates the elements of the personal protective equipment (PPE) to be used in a biogas plant. Each of these elements ensures protection against one or several hazards. They must only we worn when the staff is directly exposed to that specific hazard.

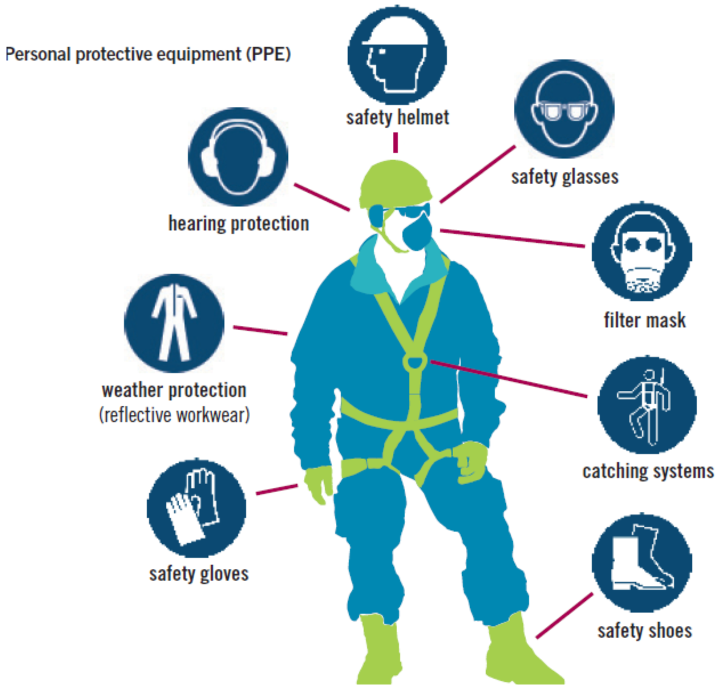

Figure 20: *Personal Protective Equipment (PPE). Source: German Biogas Association* (FvB)

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7 MCR: Measurement, Control and Regulation Technique

One of the main facilities for highly efficient biogas processes is the measurement, control and regulation technique (MCR). It is the central unit for biogas plants where all measured data come together, are recorded and checked and which alerts if data values are not within the allowed range. Measured data are usually:

- Weight of feedstock within the feeding system and fed into the digester
- Pumped quantities (from slurry tanks into digester, between digesters and handed over digestate, added liquid additives)
- Level within digesters (sensors are on bottom and on top)
- 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, course (m^3 per time unit) and composition (CH_4, CO_2, H_2S, H)
- Actual current consumption of agitators
- Lower explosion limit within rooms where gas pipes are installed
- Self-consumed energy (electricity, heat)
- Produced energy (electricity, heat, biomethane)
- CH_4 and partially H_2S in rooms where biogas might occur.
- Pressure inside the digester

Measuring CH_4 and H_2S in rooms where biogas might occur is usually requested from the permission authority and is therefore obligatory. The other above listed parameters are not always measured in all biogas plants. Usually the bigger a biogas plant is, the more parameters are measured. This is the case because bigger biogas plants have higher investment costs already and thus, the additional investment needed specifically for measurements is low compared to the overall investment.

The measured data is recorded, analyzed and with an interface the data can be stored externally and is usually used for further evaluations. With the MCR unit more and more facilities in a biogas plant are steered automatically. Some devices like 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. Via interfaces they are connected to the main MCR technique and can also be steered from there. Additionally, for some devices like the feeder, pumps, agitators etc. it is beneficial to have main steering buttons directly at the device. MCR technique can also have a remote control so that main process parameters and functions can be seen and steered from the outside.

7.1 Measurement of process parameter

As anaerobic digestion is a biological process, steering an effective process that operates almost at the limit is challenging. Several research programs were carried out to determine absolute characteristics and limit values for a proper process. Measuring the pH value would be easy, but takes some time and hence, does not give feedback about process disturbances early enough. Each biogas plant develops its own adjusted biocenosis and has its own

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composition of volatile fatty acids. Thus, it may be the case that one biogas plant operates at full capacity and performs well, while another plant with the same concentration of volatile fatty acids phases has huge biological problems.

Nevertheless, the absolute fatty acid concentration is one of the main characteristics determining process disturbances. Not only the absolute content of each important fatty acid is important, but also the changes over time.

Unfortunately, it must be considered that determining fatty acids is still not available as online determination (except from a gas chromatograph which is too expensive for this purpose) and needs to be done in an own or external laboratory. Hence, many operators send samples for analyzing the fatty acid content to external laboratories multiple times a year. This is often done in combination with feedstock analysis, nutrient and micronutrient content analysis. A high total volatile fatty acid (VFA) content shows that maybe methanogenic bacteria are inhibited. A further raise of VFA would cause a drop of pH value. While the hydrolytic and acidogenic bacteria would still increase their growth within this condition, methanogenic archaea would at least stop their activity at low pH values. In consequence, a negative cycle would start because the hydrolytic and acidogenic bacteria produce even more organic acids which lowers the pH value even more which in turn inhibits the activities of the archaea. The total volatile fatty acid content therefore should not exceed 4 g l^{-1} expressed in acetic acid equivalent. An optimal pattern for VFA shows higher concentration for lower VFA (acetic acid, propionic acid) compared to lower concentration for longer chain acids. acetic acid equivalent. If longer chain VFA raises compared to acetic acid, the process may be inhibited. (Herrmann C. 2020, Kaiser F. 2010).

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

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.		

As the substrate used in biogas plants usually has a high buffer capacity, the determination 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 not drop, although acid concentration raises, and the process may still run effectively. Several studies searched for possibilities to find an easier and even more precise diagnostic method for determining the process stability. At the end a method was develop called FOS/TAC. 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 sets determining the FOS/TAC value. Values around 0.4 are fine, while values above 0.8 show process disturbances. If the latter occurs feeding shall be lowered or even stopped until the reason for the process distortion is found and fixed. It must be considered that the effectiveness of this method is still under discussion and again these values cannot be seen absolute as each plant has its own biocenosis.

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7.2 Measurement of foam

Another very disturbing effect for the performance is when foam appears at the substrate surface within the digester. This effect can have many reasons ranging from the change to high energetic and fast degradable feedstock, lack of micronutrients, temperature fluctuations to several process inhibitions through surface active agents (tensides). If the foam building process cannot be stopped immediately, it often ends almost in a standstill of the biogas process. As foam may get into gas pipes etc., it also causes secondary damages. If substrates are used which may cause foam (protein rich feedstock) a surface detection should be installed (ultrasonic), the micronutrient content should be determined more frequently, the feeding should be done hourly and other technical disturbances such as temperature fluctuations should be avoided. If foam occurs nevertheless, one of the fastest countermeasures is to stop feeding, to start stirring, to lower the filling level within the digester and to pump in already further digested substrate from the post digester or from the storage tank. For the latter, it is important not to change the temperature within the digester with this action as this would cause further process inhibition. Also, anti-foaming agents can be used. However, it is important that these anti foaming agents do not create siloxane (Kliche, 2017).

7.3 Measurement of the gas, quality and quantity

The quality of the gas says much about the stability and sanity of the biological process and of course about the energy produced. Thus, all biogas plants are equipped with a device that analyzes gas. It shows the composition of the biogas and gives information about the following:

- CH_4: Is the most valuable component. The higher the CH_4 content, the more energy is in the gas;
- CO_2: the relationship of CH_4 and CO_2 is important in order to determine the stability of the biological process. The CH_4 concentration should be higher than the CO_2 concentration. Changes in the relationship indicate unstable process conditions;
- O_2: indicates if leakages in the gas system occur. If above 1%, the operator should do a leakage control;
- H_2S: toxic and corrosive gas. Can occur in a range of below 100 ppm up to several thousand ppm (mainly depending on the quality of the feedstock). Should be as low as possible. Usually the technical equipment defines to which level H_2S should be reduced. Typical limits for CHP operation are in a range of 50 - 200 ppm;
- H_2: measurement for process optimization.

Excurse, 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 promptly shows a process distortion (BMWFW, 2017). Here, the methanogenetic process is hindered while the first steps of biomass degradation are usually not disturbed. The latter would cause an ongoing acid production while these acids are not transformed to methane anymore and so the pH value will drop. Therefore, the check of the hydrogen content in the biogas is one of the fastest possibilities to monitor if there are possible process disturbances. As with other biological processes, not the total amount of hydrogen is the indicator, but the changes within short periods.

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Flow meter

The flow meter measures the volume rate of the biogas production, typically in m^3/h. This value shows whether the biological process is stable. If this value drops, the living conditions for the microorganisms are not optimal anymore and measures to stabilize the process are important.

Additionally, the biogas production rate indicates if the whole biogas plant operates in an efficient manner and whether the gas yield is according to what is expected from the feedstock used.

7.4 Documentation of data

Over the past years it became more and more important to have a proper data recording, also due to legal requirements. Many legal institutions that are responsible for the permitting procedure and for recurrent inspections of biogas plants request several data to be recorded and additionally demand recurrent self-checks and external audits done by professionals.

Keeping record of self-checks done on safety devices, performed maintenance and external audits done by professionals became more and more important.

While data that are usually measured by the MCR technique are also recorded by that same technique, all other recording needs to be done in a separate logbook. Some MCR techniques also provide a tool to include these data or at least provide a scheduler to set a reminder.

To give a visual impression of how those MCR techniques look like and to allow for a better understanding, some photographs are presented below.

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).

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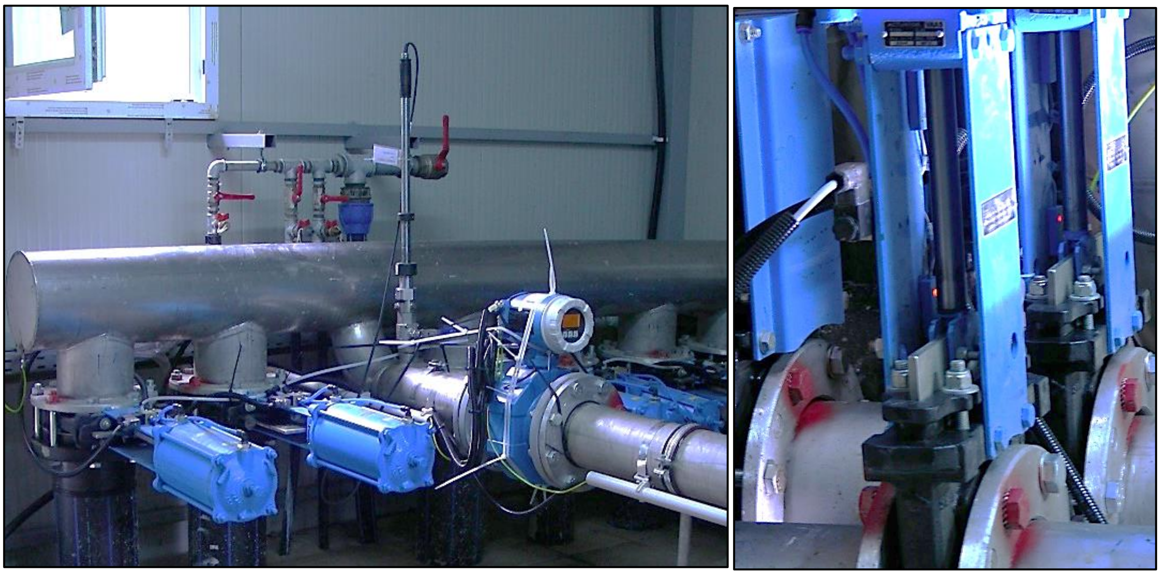
Picture 47: Pumping station with pressure sensor before and after the pump to detect distortions.



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

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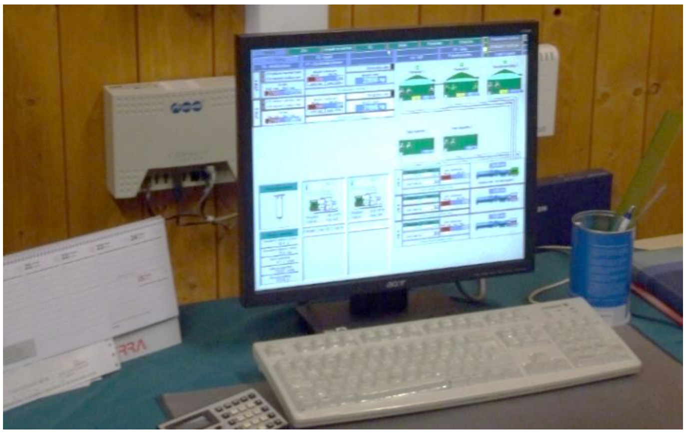
Picture 49: Biogas analysis to detect CH_4, CO_2, H_2S and H.



Picture 50: Visualization of the MCR.

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

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8 Digestate Storage and Use

The most recognized product of anaerobic digestion is biogas. However, the second product, digestate (digestate is the effluent of a biogas plant), is also very valuable. AD can be seen as one of the most important techniques that combines renewable energy production with nutrient recycling. Biogas consists mainly of methane, carbon dioxide and very few amounts of hydrogen sulfide and nitrogen. Thus, with the gas mainly carbon, hydrogen and oxygen and only traces of other substances are leaving the biogas system. Nearly all nutrients from the feedstock are remaining in the digestate. Therefore, digestate includes almost all nutrients that came into the process with the feedstock and it can be considered as full compound organic fertilizer. Depending on the feedstock used, also considerable amounts of carbon cannot be degraded and formed into biogas and therefore remain in the digestate as well. Examples include lignin and celluloses which are not or barely degraded in biogas plants and remain in the digestate. These amounts of carbon are valuable sources for humus formation on the field.

For example, phosphorous is one of the essential macronutrients for plant growth and seen as finite resource. Therefore, phosphorus is already seen as critical raw material (COM/2017/490 final), but still gets lost via landfilling and incineration of all kinds of organic waste streams and sewage sludge. This loss of phosphorous will become more and more important in the future. To support nutrient recycling from organic streams, the European Union started a process streamlining the legal situation of nutrients from organics at the beginning of the last decade.

With an amendment, digestate is now included in the EU fertilizer regulation (2019/1009/EG) and could become an EU fertilizing product that could then be sold across borders within the EU without any further restriction. It is important to notice that the moment digestate becomes a fertilizing product under EU fertilizer regulation, it automatically ceases to be considered as waste (Article 19). Furthermore, after setting specific rules for animal byproducts within Article 46, digestate from animal byproducts ceases to be considered as animal byproduct. Additionally, an amendment of Annex V of the REACH regulation (Registration, Evaluation, Authorization and Restriction of Chemicals, 1907/2006/EG) was made. Trough Article 12 of Annex 5 it was clarified that digestate does not have to be registered under REACH anymore.

An advantage of the use of digestate is that the farmer can reduce the money spent for synthetic mineral fertilizer and/or can expect higher crop yields if digestate is used. The following example might illustrate this advantage: The development of biogas plants was mainly driven by European organic farmers in the 1970 and 1980ties (before renewable energy production was supported by the governments). They were not allowed to use synthetic mineral fertilizer on their farms. By operating a biogas plant, they produced their own fertilizer and higher crop yields were achieved. Hence, producing fertilizer may be a huge motivation for many farmers. This aspect is very important especially in low fertilizing systems which are very common in some developing counties, e.g. practiced by many farmers in Africa.

8.1 Properties and ingredients of digestate

Depending on the feedstock used and the technique applied, the quality of digestate can vary significantly. The following table shows the main characteristics of raw digestate from some example analyses.

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

	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

For plant nutrition it is also very important 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 solved in the liquid (like K) while others (like P) are mainly in the solid phase of the digestate.

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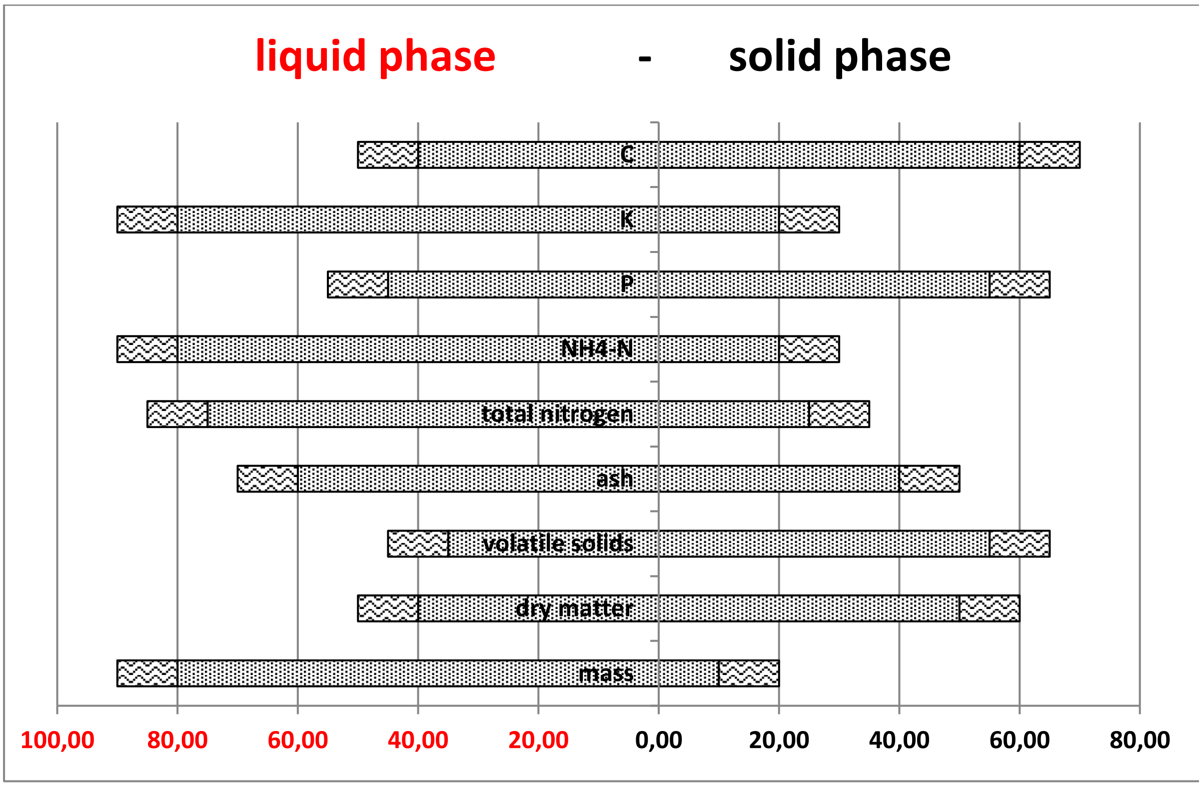

Figure 22: Distribution of nutrients and other relevant parameters between liquid and solid phase of raw digestate [%]; © Fuchs 2010.

Digestate can be further treated, i.e. technically upgraded. With upgraded digestate, concentrated fertilizer can be produced (which can be better transported). Furthermore, a separation of the liquid phase (to be spread on the fields) and the solid phase (to be composted) can be done. So far, the most common techniques used for upgrading digestate are by screw press or decanter. Currently, those are the most developed, the most reliable and the cheapest techniques available. Due to the growing size of average biogas plants, due to an increasing amount of plants and due to the huge efforts made for a circular economy, further upgrading techniques are currently being developed.

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

	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

Further information about digestate, digestate use and upgrading can be found in the publication from Fachverband Biogas: *"Digestate as Fertilizer"*.

8.2 Hygienic benefits of digestate

At the beginning of the biogas market development in Europe, the discussion came up of whether digestate might cause cross contamination of different kinds of diseases. As many biogas plants are operated by different types of cooperation between farmers it became evident that there is a strong need for scientific clarification of whether digestate can cause any spread of diseases. Through the used energy crops, straw, crop residues, vegetable waste etc., also weed seeds, unwanted plant propagules from weeds and plant pathogens could come into the digestion process. In order to clarify whether weed seeds, plant propagules or plant pathogens can pass the digestion process without losing its germination respectively sprouting ability, several studies were done (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-days digestion process at 35 °C and is destroyed after a retention time of seven days. To sum

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it up, the study demonstrates that with a proper digestion process (with a retention time over 7 days and at least 35 °C digestion temperature), the germinability of weed seeds is no problem anymore.

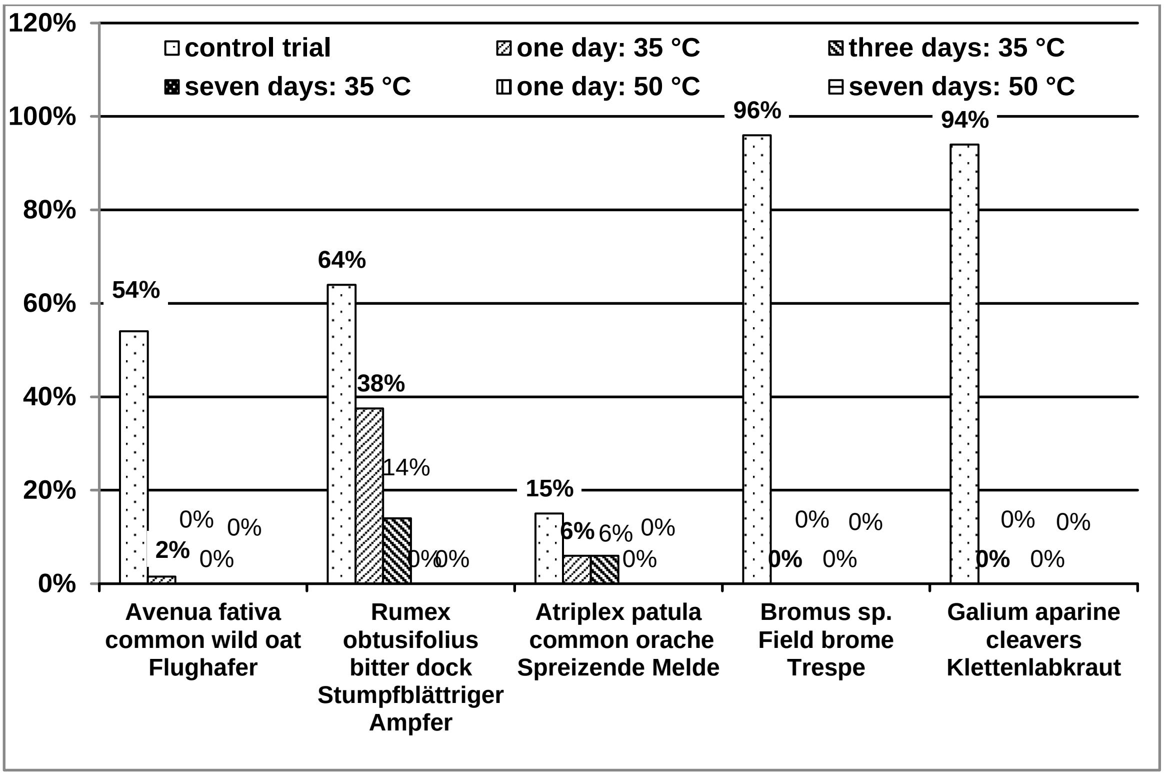

Figure 23: Germination ability of different kinds of weed seeds by 35 °C and 50 °C digesting temperature and depending on the retention time; © Pfundtner 2010.

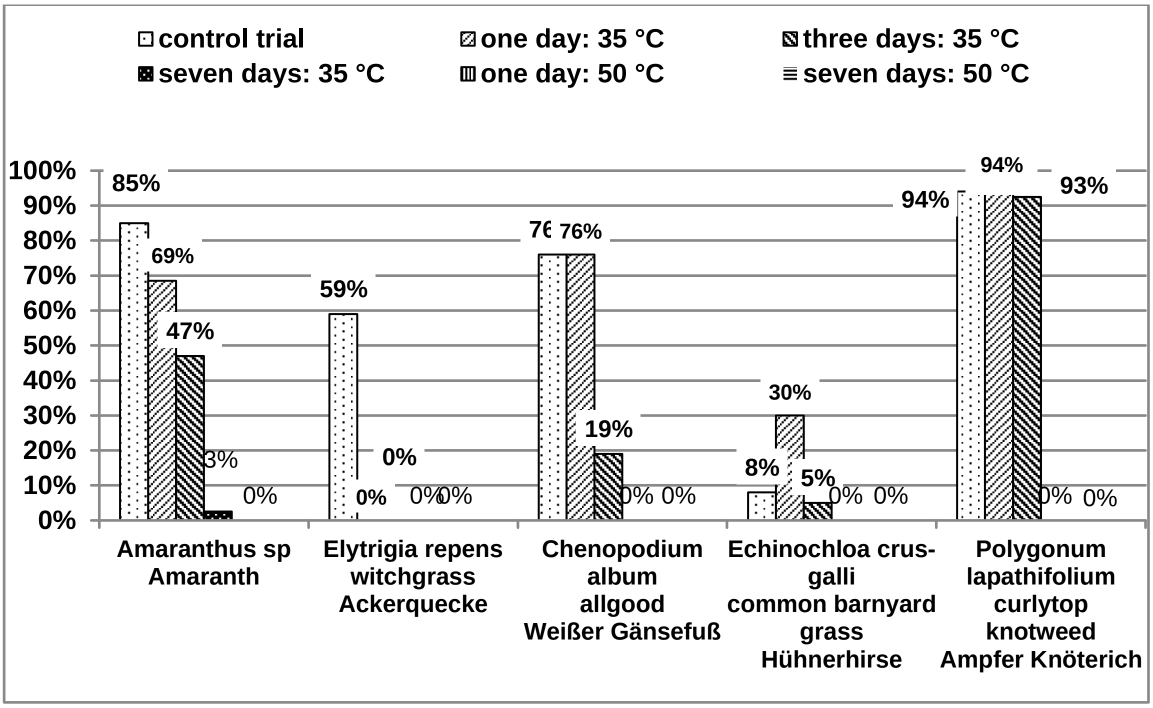

Figure 24: Germination ability of different kinds of weed seeds by 35 °C and 50 °C digesting temperature and depending on the retention times; © Pfundtner 2010.

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

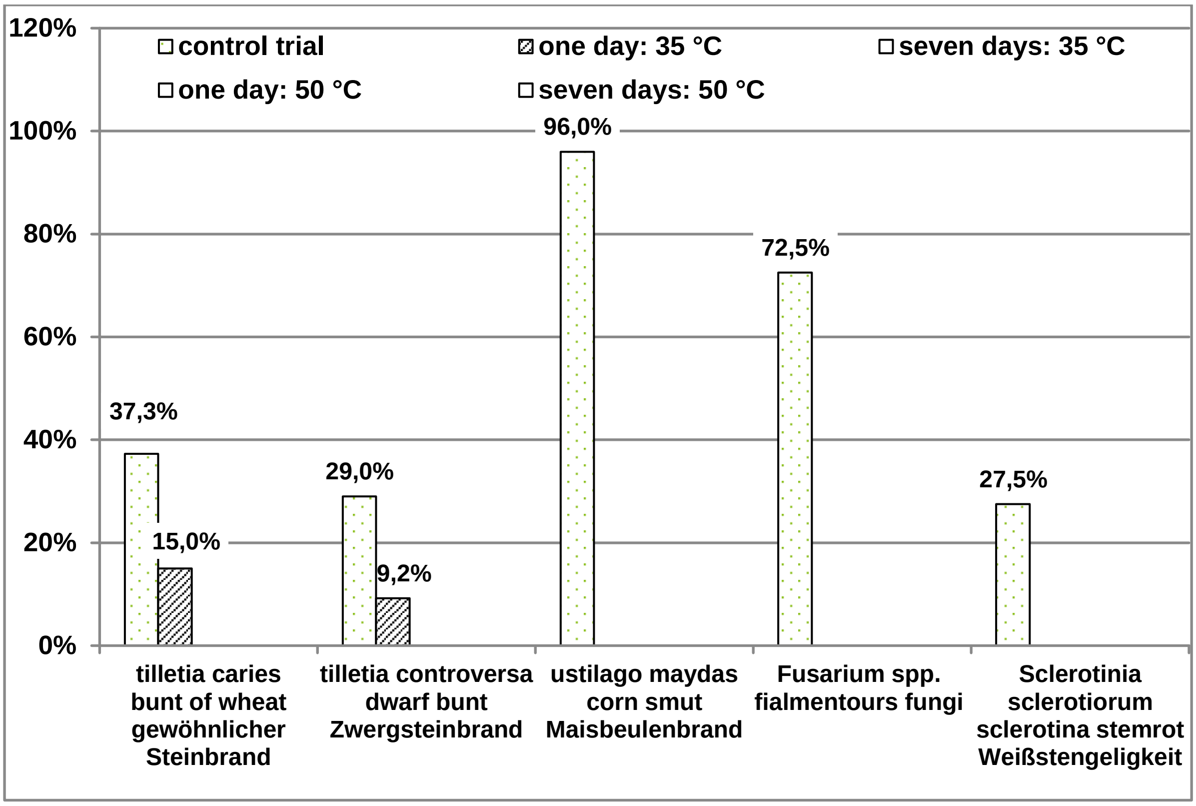

Figure 25: Viability of different types of pathogens in digesters operated by 35 °C and 50 °C after a one-day and seven-day retention time; © Pfundtner, 2010.

In the same report, the Austrian Agency for Health and Food Safety 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.

Additionally, a 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 elaborated a brochure specifically on this topic by summarizing several studies. The results (summarized by Lukehurst, Frost, & Al Seadi, 2010) show that eggs of common gastrointestinal worms and larvae of lungworm were inactivated after an eight-days retention time with a digestion temperature of at least 35 °C. Increasing the temperature to 53 °C would induce an inactivation already after less than 4 days. Many common viruses, e.g.: bovine viral diarrhoea (5 minutes at 55°C; 3 hours at 35°C) and Aujeszky's disease in pigs (10 minutes at 55°C; 5 hours at 35°C) and Johne's disease in cattle (M .Para tuberculosis after 0.7 hours at 55°C, 6 days at 35°C) died already under mesophilic conditions in the anaerobic digester.

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Further studies show that in case there are pathogen bacteria in the feedstock, they will be reduced during the process. This was investigated for several stems of bacteria. The reason is probably that the bacteria inside a digester are adapted best to the feedstock that is fed into the digester. Those bacteria that degrade sugars, fat and proteins are dominant in the process and pathogen bacteria do not endure the concurrency with the well adapted (not pathogenic) bacteria.

However, if very high amounts of pathogen bacteria are fed into the process, they will only be reduced, but not eliminated completely. Most types of biowaste and animal by-products (e.g. slaughterhouse wastes, household wastes, meals from canteens etc.) need to be sanitized in order to eradicate or reduce animal pathogens to an acceptable and low sanitary level. This does not apply for manure which can be spread directly on the fields for as long as digestate from manure is not listed under EU fertilizer regulation.

There are several techniques of sanitisation including the following:

- Pasteurization 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. Pasteurization can be done upstream for only the fraction of waste that might contain pathogens. The heated material also helps to transfer the heat to the subsequent digestion process. Another method is to pasteurize all digestate. However, the fact that all digestate must be treated (not only the contaminated part) makes this procedure disadvantageous as it is more expensive and needs 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 if the material is sanitized 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 sanitization, these methods can be accepted as well.

8.3 Benefits of digestate as organic fertilizer

For the plant operator and for appliers of digestate, the effect on soil microbes and aggregate stability is of high importance. In order to understand the different impact on soil microbes etc. by digestate and by untreated raw farm fertilizer, a closer look into the digestion process is needed. Besides degrading carbon and building up biogas from it, microbes also degrade unwanted volatile organic compounds (e.g. iso-butonic acid, butonic acid, iso-valeric acid and valeric acid, along with at least 80 other compounds).

If untreated, the latter would cause an unpleasant odour when released to the atmosphere and would also have a negative impact on the soil microorganism. The following figures show the degradation of organic compounds within the digestion process, a comparison of GHG emissions by untreated and by digested farm fertilizer and the reduction of several types of volatile fatty acids during the digestion process.

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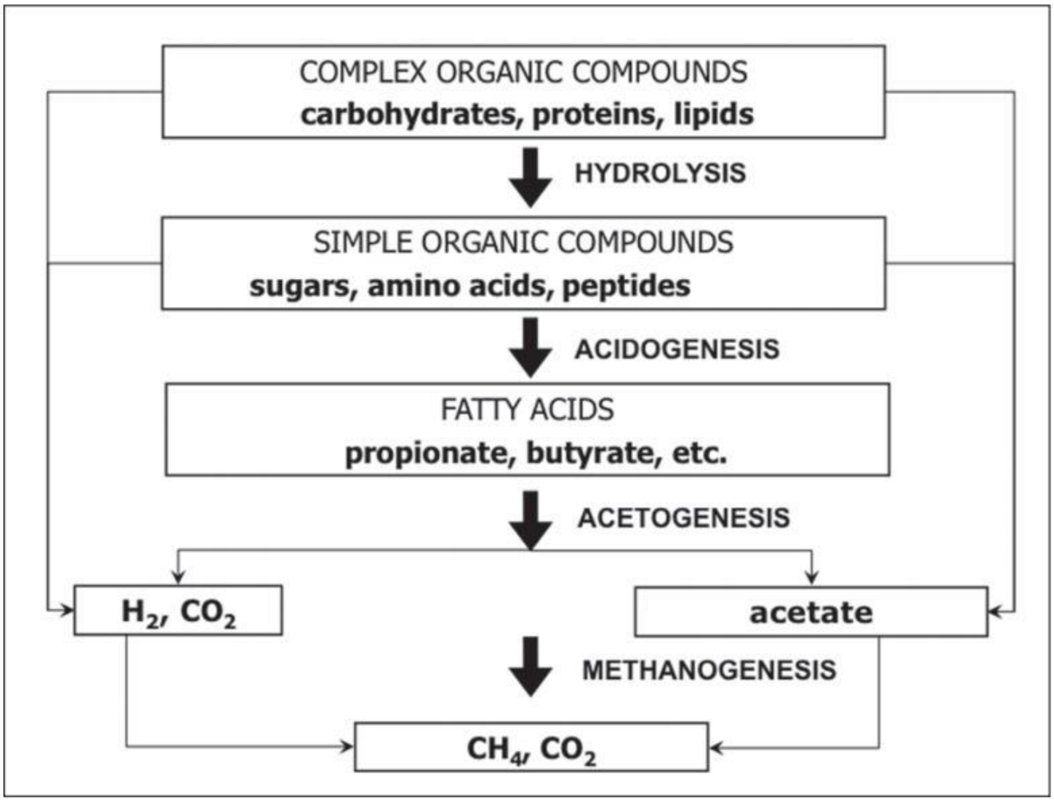

Figure 26: Degradation steps of organics within the anaerobic digestion process; © Drosg 2013.

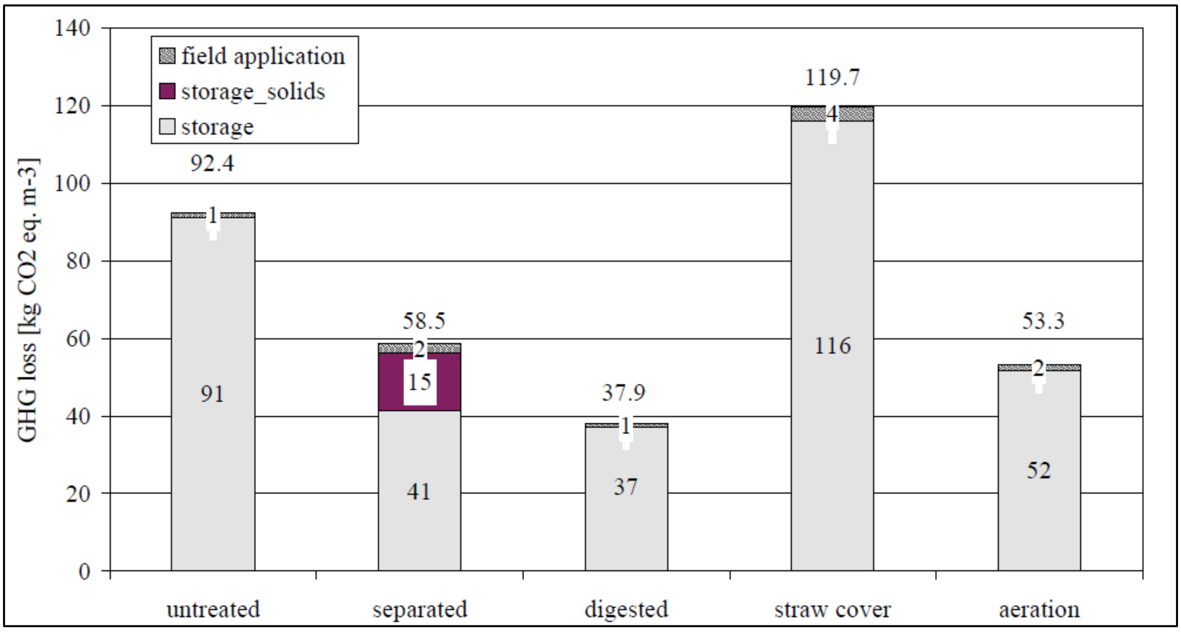

Figure 27: Greenhouse gas emissions during storage and after field application of dairy cattle; © Amon 2002.

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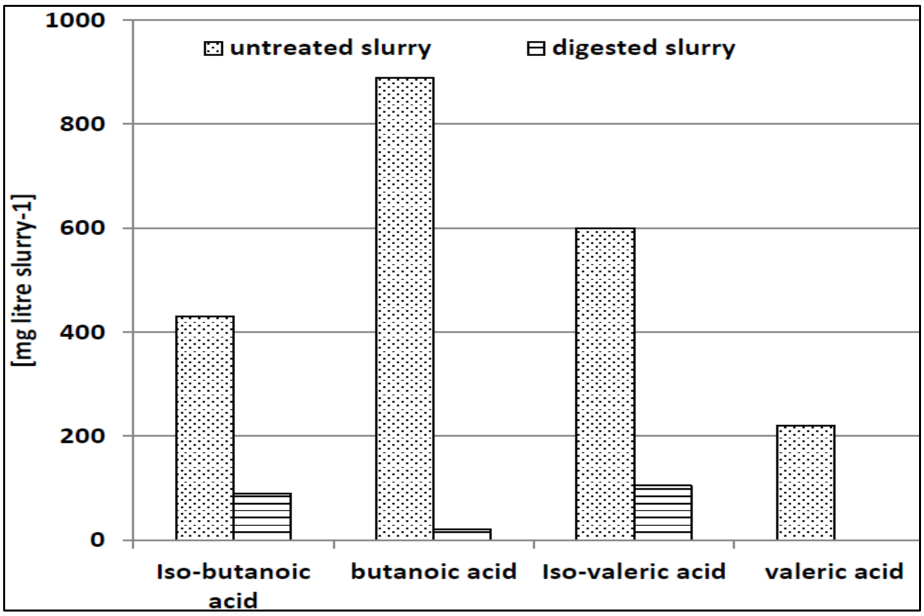

Figure 28: Concentration of different kinds of volatile fatty acids in raw farm fertilizer and digested farm fertilizer; © Hansen 2005.

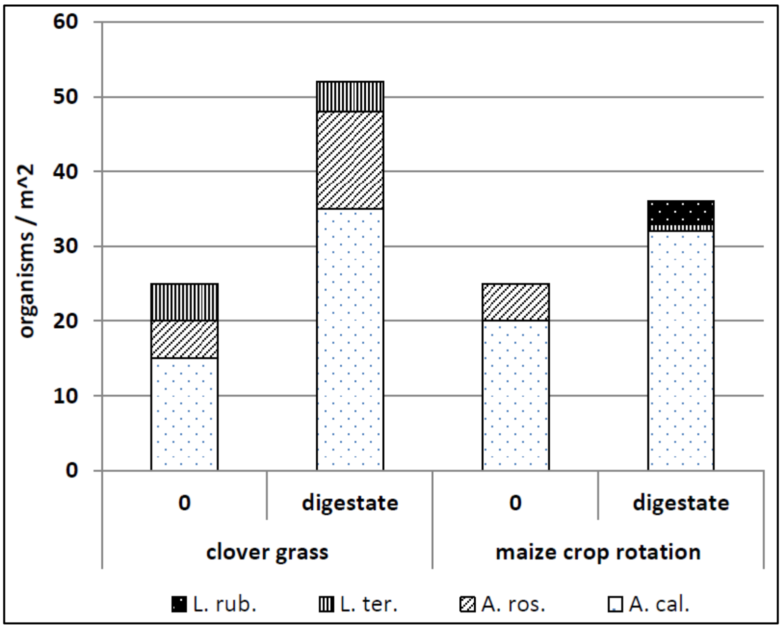

Figure 29: Presence of different kinds of worms in soil without application of digestate (=0) and with application of digestate to different crop rotations; © Hülsbergen 2016.

Due to this positive effect of digestate on soil microorganism, we can also expect a positive impact on the aggregation stability of soil. This was investigated by Hülsbergen 2016 and is shown in the next figure 30.

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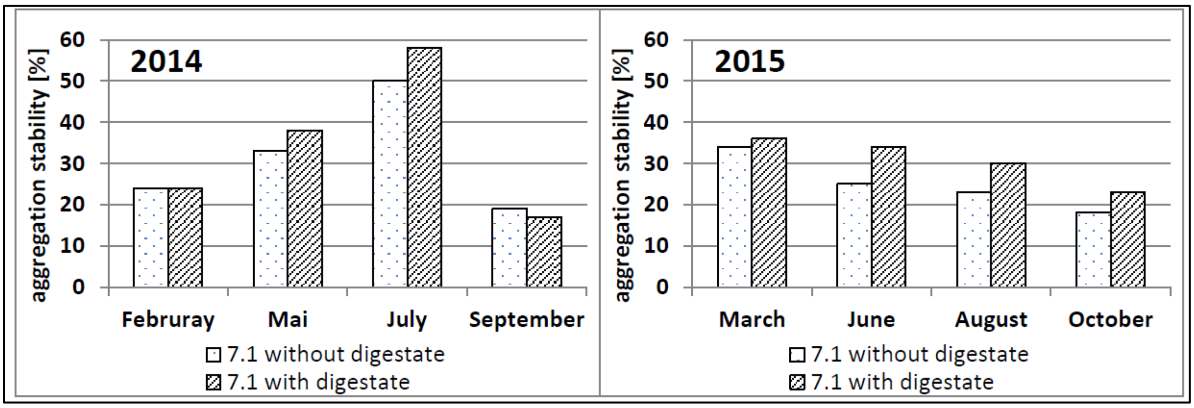

Figure 30: Comparison of aggregation stability of soil without application of digestate and soil aggregation stability with application of digestate; © Hülsbergen 2016.

In his research Petz (2000) comes to the same conclusion. He discovered a significant increase of the microorganism population, a higher aggregation stability and a significantly higher field capacity of around 13% thanks to the perennial application of digestate. The latter can be very important when looking at the climate change and the associated change of whether (intensity of rain and annual rainfall). Another reason why digestate has a positive effect on soil is its humus forming capacity. With his research, Reinhold already showed in 2008 that digestate has a very important capacity in forming humus (as shown in Figure 31). Nielsen et al. also compared carbon stability after application to silty sand in 2018. Within 500 days carbon from bovine manure had the lowest mineralization rate (15%) while carbon from different kinds of digestate mineralized between 25-47% (but was still below bovine slurry with a mineralization rate of around 50% and wheat straw with a mineralization rate of nearly 70%). Digestate significantly improved the aggregate stability of the soil, comparable to bovine slurry and a bit above bovine manure.

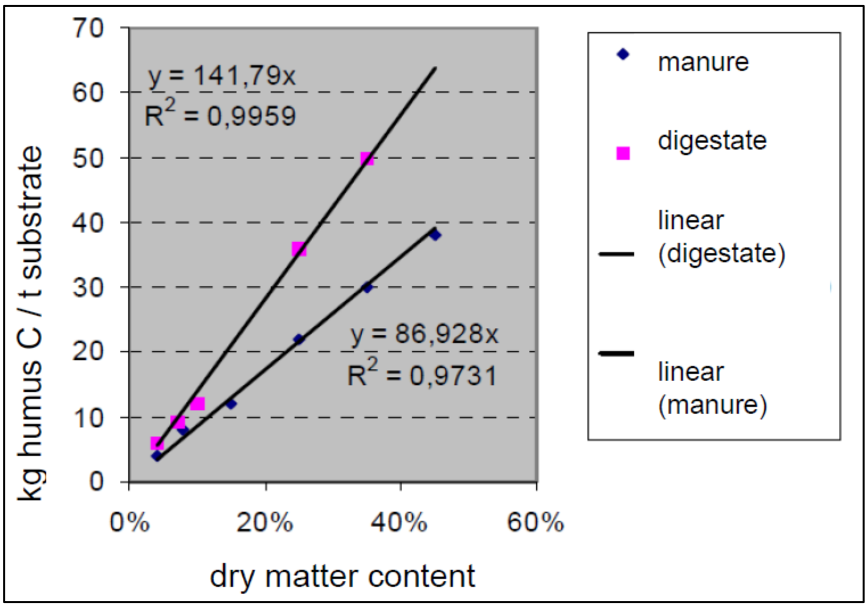

Figure 31: Comparison of humus forming possibilities of untreated manure and digestate; © Reinhold & Zorn, 2008.

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

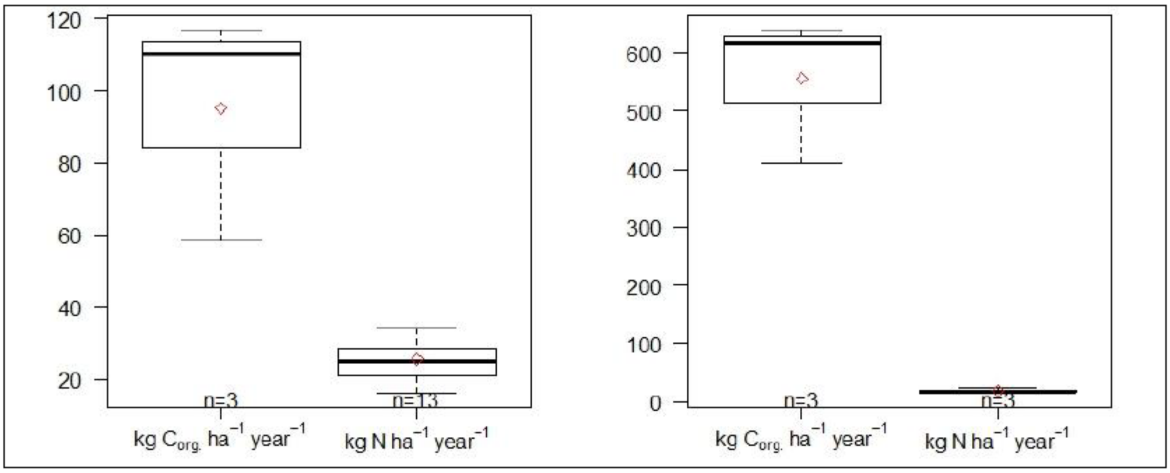

Figure 32: Rotting process of catch crops during winter periods: left: losses of $C_{org.}$ and N per ha into ground water; right: losses of $C_{org.}$ And N per ha into atmosphere; © Szerencsits 2014.

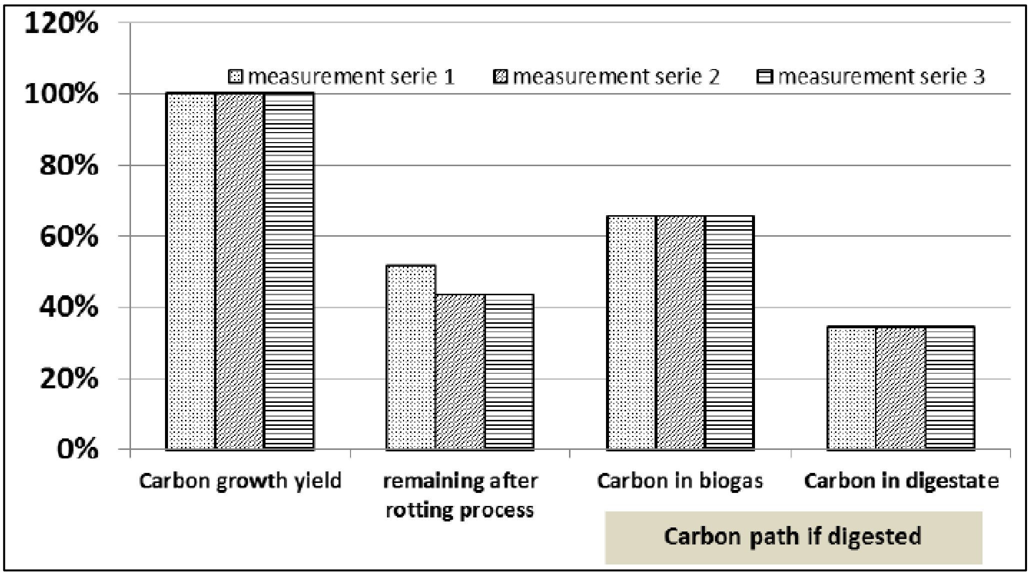

Figure 33: Comparison of Carbon path from catch crops: a) catch crops stay on the field to rot, b) growth of catch crops are harvested, digested and digestate is brought back to field; © Kirchmeyr 2016.

Important to notice is that N will be fixed during the digestion process and therefore losses can be minimized. All in all, reaching high yield second crops may help significantly in avoiding wind and water erosion, raising soil fertility and combined with anaerobic digestion additional energy can be produced and nutrient losses minimised.

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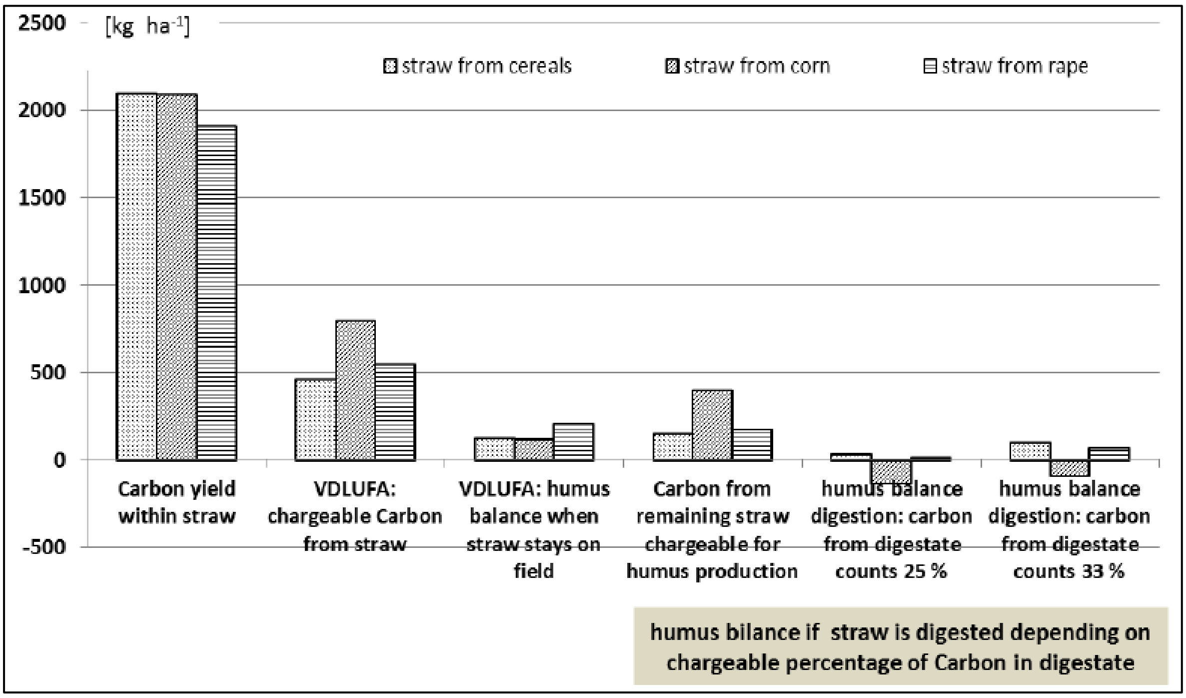

Figure 34: Humus forming ability of rotting process of straw compared to harvesting and digesting straw; © Kirchmeyr, 2016.

Depending on the calculation method for humus balance and here especially of the factor for the humus forming capacity for 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 fertilizer for plant nutrition, the aspect of possible impurities needs to be considered. When the used feedstock comes only from pure fractions like energy crops, straw, farm fertilizer and by-products from food, feed, beverage and renewable transport fuel, this aspect is less important. However, when organic waste streams from households, catering, sewage sludge etc. will be digested, a closer look on possible impurities is needed. Problematic impurities might be plastic, metal (especially heavy metals), glass, antibiotics, pharmaceutic residues and other chemicals that should not, or at least only to a minor degree, be spread on fields. Within the EU, the special requirements in Annex II of the recently amended EU fertilizer regulation (2019/1009/EG) have to be fulfilled.

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

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	

Each digestion plant, treating organic waste that might include impurities, uses an impurity removal device before the digestion process. However, it might be necessary to perform a second check in order to ensure that the above listed requirements from the EU fertilizer regulations are fulfilled. Another reason for this second step is that no plant operator wants to spread undesired impurities on agricultural fields. Such an additional step is usually done by sieving the whole digestate directly before it flows into the storage tank. Several investigations of digestate demonstrated the efficiency of this device.

When animal by-products are fed into the digester also a sanitation step is required. This is usually done *before* the substrate is fed into the digester. The reason behind this is efficiency and a kind of pre-treatment of feedstock during the sanitation process that allows for a faster degradation of organic material within the digestion process.

In special cases it could also be done *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 remaining biogas will be collected.

8.4.1 Separation, drying and further upgrade

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

- Producing recyclate which is needed to avoid too high DM content in the digester
- Producing a solid phase which can be sold to consumers
- Producing marketable fertilizing products

The most common technique to dewater digestate is by using a screw press.

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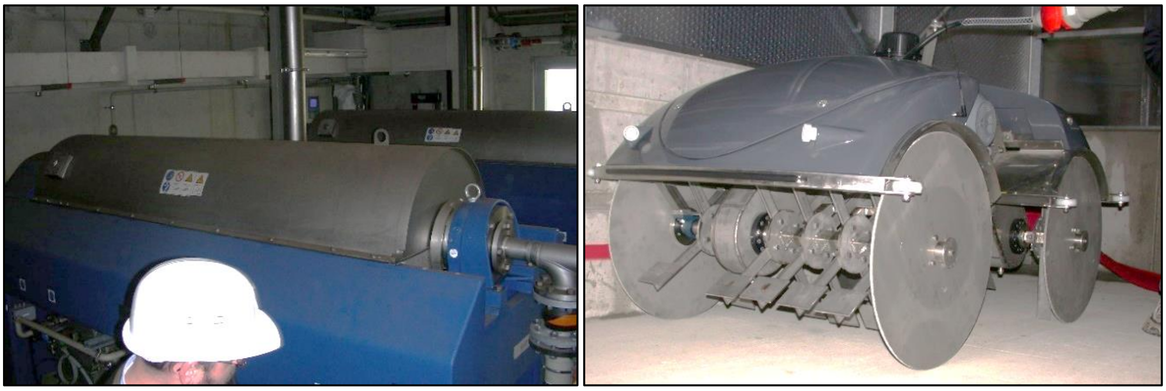
Picture 51: Screw press to dewater digestate.

Also applied in warmer regions are sun-drying systems where the digestate is filled into a glass house and is turned via automatically driven turner. Important is that during the drying process also ammonia and other gases, like N_2O might be released. These emissions should be limited because some gases are potential Green House Gases, like N_2O. Ammonia losses should be limited because a loss of ammonia is also a loss of nitrogen which is an important fertilizer.



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.

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Also used in practice are dryer belts through which the digestate is dried with warm exhaust air from the CHP. The dried digestate can be pelletized and sold for small gardening etc. As ammonia will go into the gas phase to some extent, it is important to remove the ammonia from exhaust air before its release into the atmosphere.

If the digestate process is done in a dry digestion process, then what follows the digestion is usually a composting process. During the last years several research programs were conducted to further upgrade digestate into a product which can directly replace mineral fertilizer. These techniques are stripping, membrane filtering, osmosis etc.

8.5 Digestate storage and application technique

As digestate is a valuable organic fertilizer, it should be applied in periods of plant growth. Depending on the climate conditions where the biogas plant is constructed, 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 (e.g. during winter season).

In Central Europe with its long winter periods, the usually required storage time is 6 to even 9 months. Most storage tanks are made by in situ concrete, precast concrete or lagoons with double membranes and tightness monitoring. Storage facilities can be built in open or airtight versions. The latter is required more and more due to possible methane and laughing gas emissions from storage tanks.

Covered storage tanks require an installed stirring system that is fixated while open storage systems often use these systems as well but can also use mobile stirring devices. Compared to the application of raw farm fertilizer, the use of digestate offers several positive effects as mentioned above. Because the percentage of ammonia within the total nitrogen content is higher compared to the one of farm fertilizer, the application should be done with devices that lower 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 vegetation season, slit injection is also an option. Additionally, the loading from storage tank into transport tanks and from transport tanks into the field-application-device should be done in closed connection.

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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.

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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.

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9 Biogas Storage

Thanks to the scientific and technical developments during the last decades, professionally operated biogas plants often run very constantly at full load capacity. This is mainly when feedstock can be stored or will be delivered constantly and therefore can be fed to exact times when needed. Such biogas plants can reach full-load-hours above 8,000 h a^{-1}. When organic residues from households, caterers or other seasonally accruing feedstock are the main feedstock, then biogas production will vary according to the delivered feedstock. This is because the amount of organic waste from households differs between seasons and carbon rich effluent from sugar plants or biofuel plants occur only seasonally etc. Furthermore, biogas application might also follow consumer needs and might also be interrupted due to maintenance reasons etc. Additionally, at times when the gas consuming application is not working, e.g. in times of maintenance, the produced biogas must be stored. This partially occurring imbalance between biogas production and biogas application is usually balanced through special gas storage systems.

The size of the gas storage system differs significantly. For plants which can use the produced biogas without restrictions, the size of the biogas storage system covers often 3 up to 10-fold of hourly produced biogas[2].

As biogas is a very reliable and flexible energy source, the focus of attention shifted also to the application of biogas balancing the electricity grid. The idea arose that biogas could also help balancing the electricity grid by producing peak load electricity or control energy or by being applied over a specific time period. Although there has been some scientific work done in changing the biogas production within the digester corresponding to the consumer demand, in the end it became clear that it is better to run the digester constantly and to store the biogas in the periods where the electricity is not requested.

These systems usually have biogas storage systems that can store the produced biogas for one day or even longer. An important consequence is that the CHP then often has the double or even 3-fold electric capacity as it would have when operated constantly. In Germany for example, there are several thousand biogas plants offering flexible operation in which the CHP can be turned on (to produce electricity) or off (to store biogas) to balance power consumption with electricity generation at a level of some 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 few millibar overpressure (depending on manufacturer and system up to 50 mbar). These types of gas storage systems can be differentiated into:

- Low pressure systems (membranes)
    - Single membrane
        - As roof of the digester
            - Self-supporting through biogas pressure (with or without outer net to shape the maximum size)

[2] For example, a biogas plant with a size of 500 kW_e has a biogas production rate of about 250 m^3 per hour. If the biogas production of 6 hours shall be stored, e.g. during maintenance of the CHP, the capacity of the gas storage should be 1,500 m^3.

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- Suspended from a middle pile
  - Incorporated in the roof of the digester and suspended it
  - Separately in-house systems
- Double membrane
  - As roof of the digester
    - Inner membranes as gas membrane
    - Outer membrane as weatherproof cape
      - Suspended from a middle pile
      - Shaped with air by an external blower
  - Stand-alone systems
    - Inner membranes as gas membrane
    - Outer membrane as weatherproof cape (shaped with air by an external blower)

There are very different kinds of biogas membrane storage systems on the market. Each manufacturer has its special system. It must be considered that compared to steel or tight-concrete systems, membrane storage systems are not completely gas-tight. Therefore, technical guidelines set requirements on permeability, tearing strength, stability to weather and especially ultraviolet radiation and aging in order to limit gas emissions and to avoid leakage.

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

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

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

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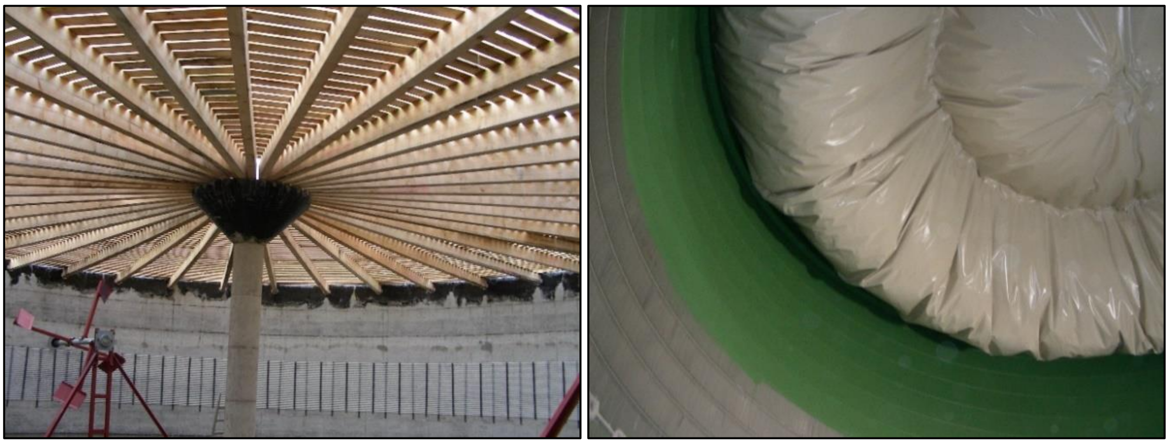

Picture 59: A view from the inside of a digester to the top, left: wooden roof under the gas membrane; right: gas membrane from the inside.

Picture 60: Single membrane gas storage in external housing.

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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.

Especially for double membrane storage systems, where the outer membrane is shaped through an air blower, the height of the outer membrane can be varied according to consumer needs. The stability against wind, weather and snow is done by the pressure of the air blower.

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

Each gas storage system also includes several safety devices in order to avoid over pressure, damage through lightning, damage through cars etc. These devices are already described in the chapter on MCR.

A special case that was commonly used in the past and is to some extent still used today is the wet gasometer. This technique was commonly used in European cities to store city gas. It is a tube filled with water in which another tube is put upside down. The gas circulates through a pipe from the bottom into the water filled tube and ends above water level. The pressure is given by the upper tube which raises during filling and lowers at demand.

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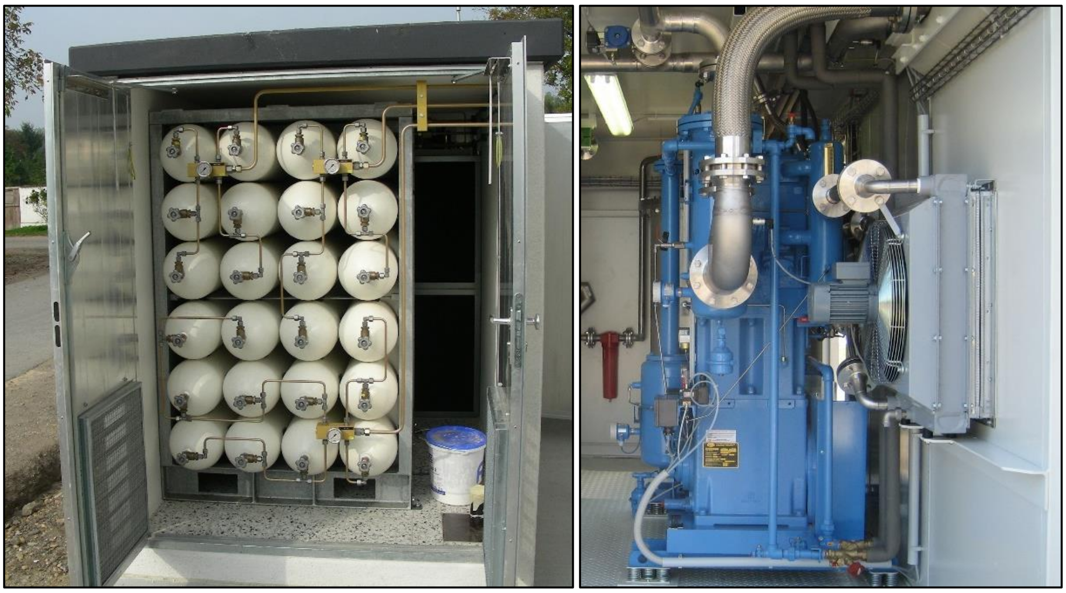
Picture 63: Wet gasometer directly included in the digestate storage tank.

- 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. E.g. for the use as transport fuel where pressure above 200 bars is required. Usually these storage tanks are made from steel. It is necessary to at least dehumidify and desulfurize the biogas as otherwise it would cause corrosion. Typically, the biogas is upgraded to biomethane quality to fill highly concentrated biomethane (without CO_2) into the gas cylinder.



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

Currently not very recognized is the option to use former natural gas caverns as seasonal storage systems. In the future, these seasonal storage capacities 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.

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10 Application of Biogas

Biogas is a very versatile renewable energy source which offers several advantages and several applications. 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
- Biomethane upgraded from biogas
  - Gas grid injection
  - Transport fuel
  - CHP: combined heat & power production
  - Heating & cooking
  - Raw material for chemical industry

The most common application within Europe is the electricity production via CHP and the use of produced heat for self-demand and district heating. However, upgrading biogas to biomethane and gas grid injection is a fast-growing market.

Produced biogas has the same temperature as the digester content and is saturated with water vapor. When biogas starts cooling, e.g. in gas pipelines, water vapor starts condensing, but biogas is still saturated with water vapor. Both characteristics can cause malfunction or even damage, e.g. when condensed water blocks the piston. Therefore, it is important to remove condensed water at the lowest point of gas pipes, to avoid that water can flow into the CHP (or other devices where it could cause damage) and to reheat the biogas before critical application so biogas will not be saturated with water vapor anymore (which could start to condense and could damage the following CHP).

The most valuable content for further application is methane, and to a lower portion hydrogen. Hydrogen sulfur and ammonia would also bring energy yield but can also cause unwanted emissions or even damage of devices. So usual biogas has an energy content between 5 and 7 kWh_{Hi} per m^3, mainly determined by the methane content. The main components of biogas are shown in table 17.

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

Component		Energy content [kWh_{Hs} Nm^{-3}]	Energy content [kWh_{Hi} Nm^{-3}]	Energy content [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

10.1 GHG mitigation potential

Biogas is a valuable renewable energy source which offers a high potential to mitigate greenhouse gas (GHG) through digesting different kinds of organic material.

In order to fight the climate change, GHG emissions need to be reduced drastically as also agreed in in the Paris Agreement. Achieving this goal requires tremendous efforts from all sectors that emit greenhouse gases. In agriculture the storage of excrements from husbandry is a predominant source of GHG emissions, but on the other side also a major source to produce renewable energy via anaerobic digestion as the following figures show.

Following the biogas production process, the GHG mitigation potential of AD originates from many pathways. Below are only a few of them described.

10.1.1 Treatment of farm fertilizer

Figures 29-31 give an overview of average daily excrements, GHG emissions and possible energy yield via anaerobic digestion of excrements from different animal species. All data are derived from National Inventory Reports of the respective countries. Firstly, Figure 36 gives an overview of the amount of daily excrements of husbandry from different European countries. Depending on the animal species, diet, climate conditions and animal performance, the amount of daily excrements from animals varies highly.

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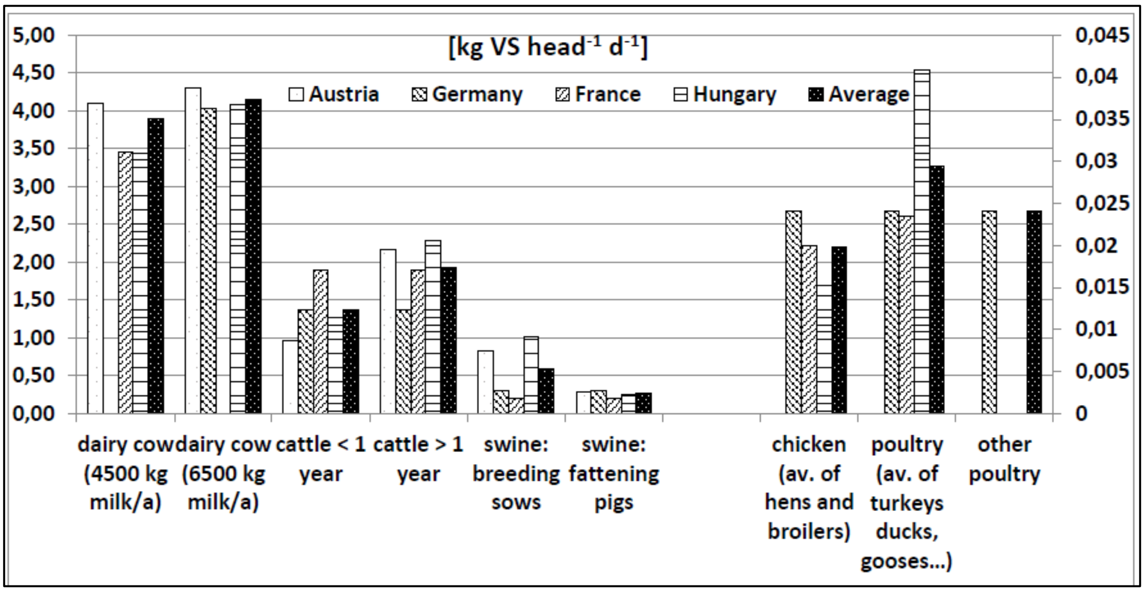

Figure 35: V_{Si} (average daily volatile solids) excreted (kg) from animal species - per country and animal category [kg VS head-1 d-1]; © Kirchmeyr 2016.

Based on excreted average daily volatile solids, climate conditions, husbandry and manure management, the average amount of CH_4 and N_2O emissions can be calculated. The latter is based on methods described in the IPPC report (IPCC - Ch 4, 2000).

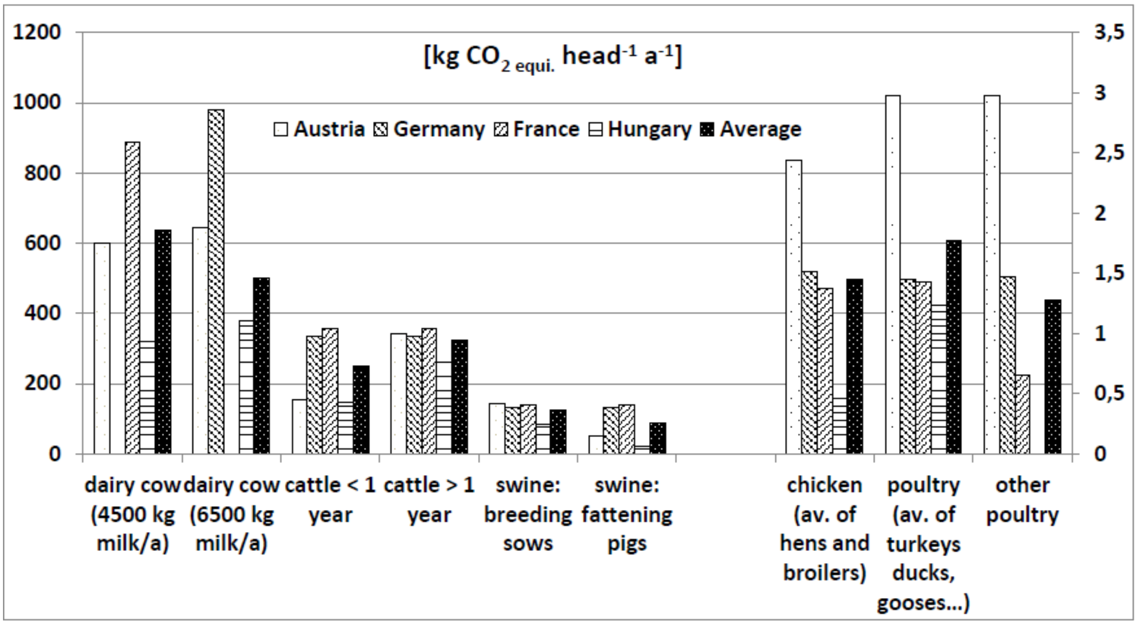

Figure 36: CO_2 equivalent emissions from slurry tanks per animal and year (considered: CH_4 and N_2O) expressed in kg $CO_{2equi.}$ per head and year; © Kirchmeyr 2016.

Instead of storing the farm fertilizer untreated in slurry tanks, it can be digested in biogas plants and used for renewable energy production. Figure 38 gives an overview of possible energy yield from farm fertilizer based on the amount of volatile solids (Figure 36) within the farm fertilizer.

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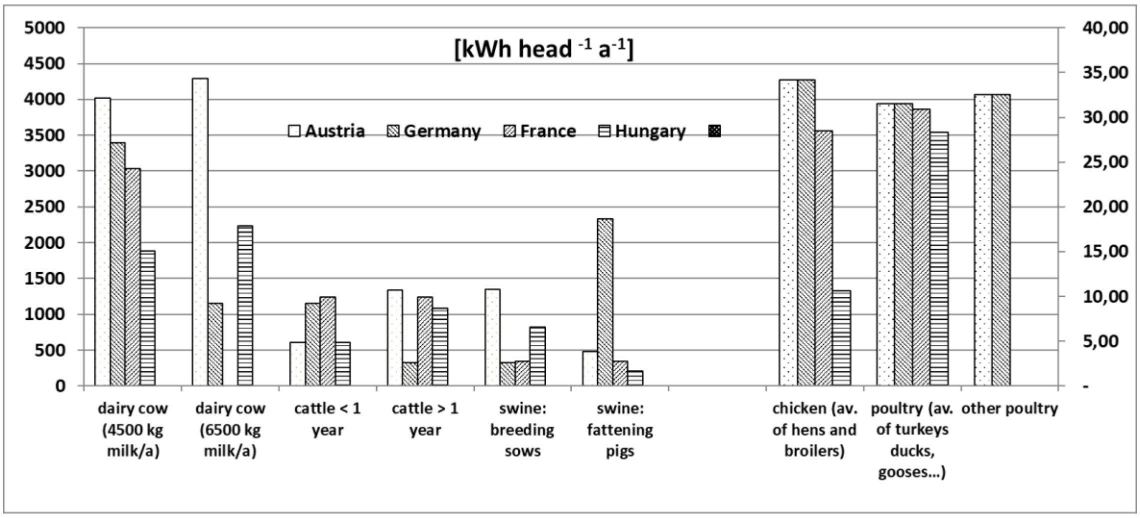

Figure 37: Possible energy yield from excrements of husbandry via anaerobic digestion expressed in kWh head^{-1} a^{-1}; © Kirchmeyr 2016.

Due to the above-mentioned effect that untreated stored farm fertilizer causes GHG emissions whereas the digestion of this farm fertilizer produces renewable energy, digestion of farm fertilizer even entails negative emissions compared to fossil fuel.

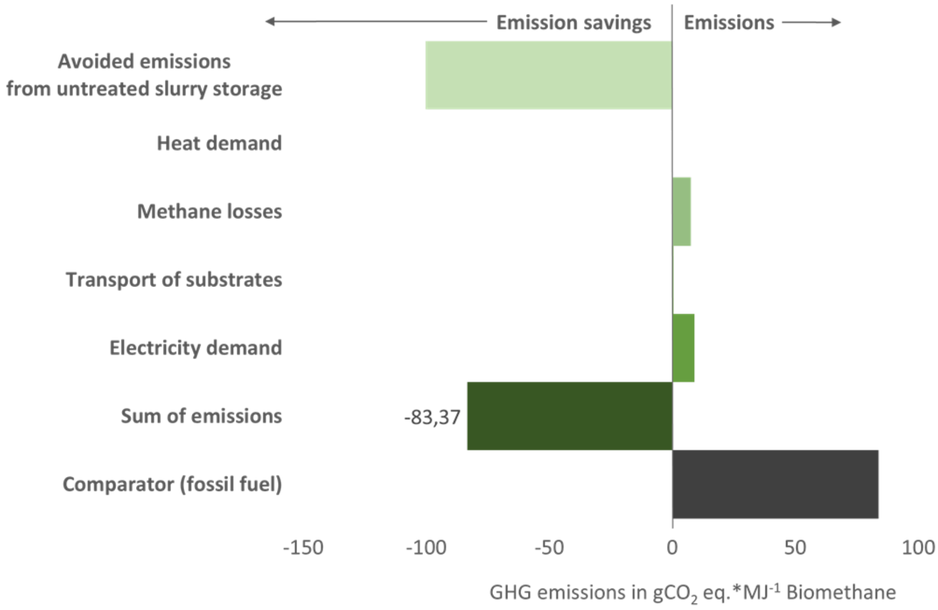

Figure 38: Sum of emissions of biomethane production from farm fertilizer compared to fossil fuel comparator of RED II expressed in g CO_{2eui} MJ^{-1}; © Mayer S. et al. 2016.

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 soil microorganism content. Compared to the use of fossil fuel, it additionally offers a great benefit on behalf of greenhouse gas emissions.

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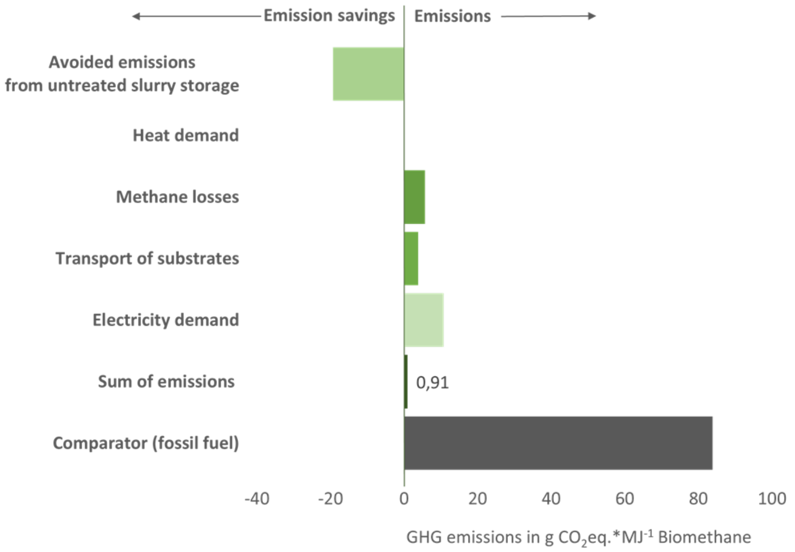

Figure 39: Sum of emissions of biomethane production from farm fertilizer and straw compared to fossil fuel comparator of RED II expressed in g CO_{2eui} MJ^{-1}; © Mayer S. et al. 2016.

10.1.3 Treatment of organic waste

While farm fertilizer and straw are typical agricultural substrates that usually stay in the agricultural circle, anaerobic digestion of biowaste offers the additional advantage to bring back nutrients for plant nutrition and replaces mineral fertilizer. Figure 33 gives an overview of the average energy demand and GHG emissions of macro nutrient mineral fertilizer production. Table 18 shows the average content of macro nutrients within bio waste from separate collection of organic waste from households.

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

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

Although nutrient recovery and especially phosphorus recycling will be a very important issue in the future, the most important driver for reducing emissions of digesting organic waste streams are the emissions avoided by landfilling organic waste. Figure 41 shows the emissions avoided when organic waste is not landfilled, the emission credits for renewable energy production as well as the emission credits for recycling nutrients. If landfilling of organic waste is banned and thus the emissions of landfilling don´t need to be considered anymore, the GHG mitigation would be 80 % compared to fossil fuel (RED II).

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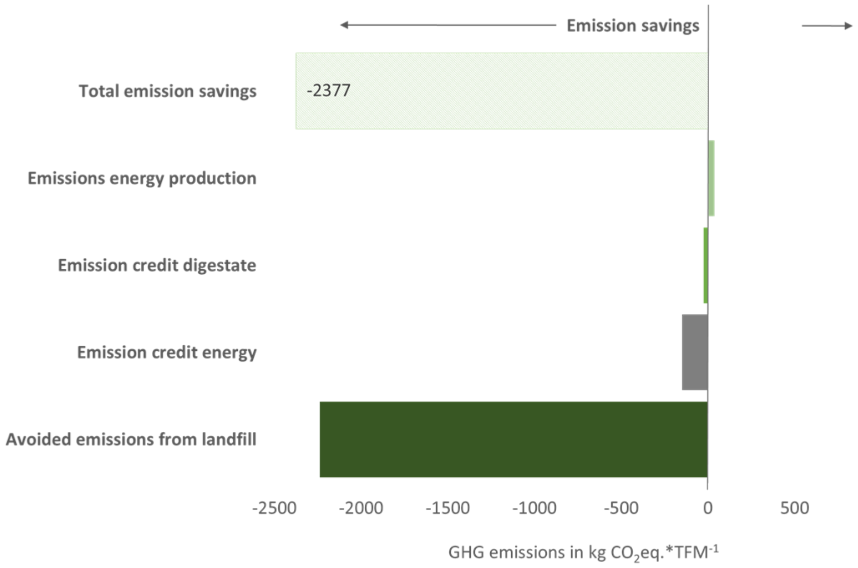

Figure 40: Emissions of biomethane production from separately collected municipal organic waste expressed in $CO_{2equi.}$ t_{FM}^{-1}; © Mayer 2016.

10.2 Application via Combined Heat & Power (CHP)

So far, biogas in Europe is most commonly used to produce electricity & heat in combined heat & power devices (CHP) directly at the biogas plant. The application to produce electricity from biogas can be done in micro gas turbines, Stirling engines, internal combustion engines or within fuel cells. Each application technique has its own special requirements for the use of biogas. To avoid damage to the application technique it is therefore necessary to check the manufacturers handbook on their special requirement. As CHP units are the most common technique for electricity production the further explanations focus on this technology.

To avoid damage to the internal combustion engine, biogas needs to be purified from possible impurities. These impurities and their amount depend, besides water vapor, mostly on the used feedstock. Possible impurities are (besides others):

- Hydrogen sulphide
- Water
- Siloxane

As sulphur is an essential nutrient of all living species, it is transported into the biogas plant with the feedstock and is partly converted to H_2S in the digester. Sulphur molecules, like H_2S cause corrosion. Each manufacturer of engines prescribes an upper limit for hydrogen sulfide. The concentration of hydrogen sulfide within raw biogas depends much on the sulphur content of the feedstock. Typical concentrations can be in a range of below 100 up to some thousand ppm. H_2S can be reduced by several desulphurization techniques, like biological conversion, chemical or physical treatment of raw biogas. The technology applied depends on the biogas plant´s design and on the used feedstock. If feedstock is used with relatively low sulphur content, biological treatment within the gas space of the digester is a very cost-efficient technique and therefore often used. Here, the bacteria Sulfobacter oxydans converts hydrogen sulfide at the presence of oxygen to elementary sulphur. The installation of equipment is simple: Just a blower that blows some air into the top of the digester is needed. Additionally, the bacteria need all other nutrient for living (given inside a digester) and a place to settle.

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Some digesters are constructed in a way to offer enough surface for those bacteria to settle. This process can also be done in external desulphurization devices. These airtight towers are filled with parts where bacteria can settle, and a nutrient solution will be spread from above to provide needed nutrients and to wash down produced elementary sulphur. Biogas is blown through such a desulphurization tower from the bottom up. A different kind of installation is chemical desulphurization. It is mostly done through adding iron compounds (iron III chloride, iron II chloride, etc.). Iron compounds fed into the liquid digester content will bind the Sulphur within digestion liquid. Chemically bonded sulphur cannot be released into the biogas. The third commonly used method is the adsorption on activated carbon. This method is typically used (often in combination with other methods) if biogas is upgraded to biomethane and needs to fulfil very low and strict upper limit values. The hydrogen sulphur is adsorbed on specially conditioned activated coal.

Biogas is saturated with water vapor and therefore it starts to condense the moment the biogas temperature is lowered, e.g. in the pipes behind the digester. To avoid water at the entry to the engine, most plants cool the biogas through pipes underneath the surface or through a water cooler. Important is that the condensate needs to 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 so the relative humidity is below 100 %. This is mostly done with exhaust heat from the blower and with a security electric heating system.

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

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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.

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

The electricity production from biogas offers many advantages: it is very reliable, storable, can be applied flexibly and offers the highest full load hours within all renewable electricity productions. A forecast scenario of future electricity production shows the very volatile production from non-biomass driven renewable electricity sources. With biogas, the production can be adjusted exactly to the current demand with peak load production and even control energy production so that the electricity grid is stable with a high security of supply.

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

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

Table 19 shows typical full load hours of biogas plants. In comparison, solar and wind power are fluctuating. As in the future, electricity should only come from renewables and here mainly from fluctuating sources, the security of supply will become a major issue and energy systems must provide electricity even when the sun is not shining, and wind is not blowing. Biogas can be stored in case there is enough electricity from wind and sun and can be used instead in times when electricity is needed.

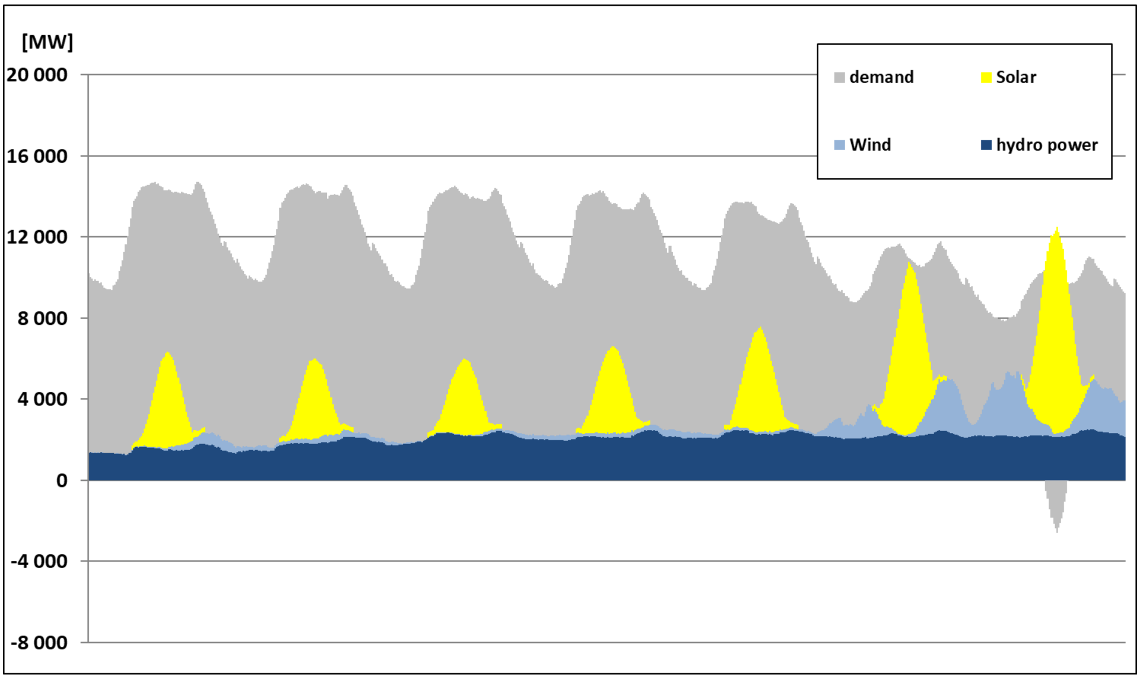

Figure 41: Forecast of Austrian electricity demand and supply from volatile renewables in week 6 of 2030; © Stürmer 2018.

Another common practice is to use CHPs for off-grid electricity production. Here, biogas can also be a good renewable source. For off-grid electricity production, the situation is like the one described above: electricity must be produced even in case the sun and wind do not provide enough energy. In practice usually an engine that is driven by diesel is installed. Biogas offers the advantage that the fuel needed for the engine can be produced with locally available resources. Additionally, a CHP driven by biogas can deliver electricity reliably which is often

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not the case in many areas around the world. There are biogas installations that were mainly constructed to avoid blackouts in the electricity grid.

The electrical efficiency of a CHP unit depends on its size and could be raised within the last two decades. Currently, the electric efficiency of a mid-size CHP is around 40%, larger units even reach an electric efficiency of the whole unit above 43%. Engines for CHP can be only driven by biogas. In this case, the ignition is done by a spark. Also, dual fuel engines are used. The ignition of the injected biogas is done by a liquid fuel which is usually around 5% of the total energy demand. The ignition fuel can be diesel or biofuel. Due to restrictions using fossil fuel as ignition fuel, the ignition fuel is typically a biofuel. The mostly used engines are single fuel engines that operate as gas-otto-engine. To produce electricity, the gas engine is coupled with a synchronous or asynchronous generator. Synchrony generators offer the opportunity that they can also produce electricity without the impulse from the electricity grid. Asynchronous generators are only used in CHP below 100 kW_{el}. As the temperature of the surrounding air has an important influence on the electric efficiency (besides other) it is important to steer the cooling air directly to the generator followed by the engine.

A gas engine must be cooled. This is typically done with a water-cooling system. As this cooling water is warmed up typically to about 90-95°C, this heat can be used, for example to heat up the digester but for many other purposes as well. Typically, this heat is used for heating houses, drying crops or wood, glasshouses or in industrial processes where heat is needed. In addition to the heat from the cooling cycle, the heat from the exhaust can be used through an external heat exchanger.

The total efficiency of the biogas plant, especially of the gas engine is depending highly 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 transferred to heat than to electricity. An efficient biogas plant should always be equipped to use the thermal energy.

It is important to follow the manufacturer´s instruction on minimum temperature of exhaust gas after the heat exchanger in order to avoid corrosion and sediments and thus damage of the heat exchanger). New CHP installations run closely to 90% of total efficiency (electricity plus thermal energy). With a special heat exchanger; also steam production is possible. Corrosion of the CHP due to impurities within the biogas is an aspect to avoid, but the coolant liquid also needs to be considered. Using only fresh water is not allowed by most of the CHP manufacturers. It needs to be desalinated and additives need to be added.

To avoid unwanted emissions, CHPs must be checked periodically and must fulfill strict emission limits. CHPs have their own measurement and steering installed in order to reach a high performance and to fulfill the requirements of upper limiting values for emissions.

Table 20: Upper limit values for new CHPs above 1 MW_{th} 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}]
Sulphur dioxide [SO_2]	40
Nitrogen oxide [NO_x]	190
Dust	-

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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

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.		

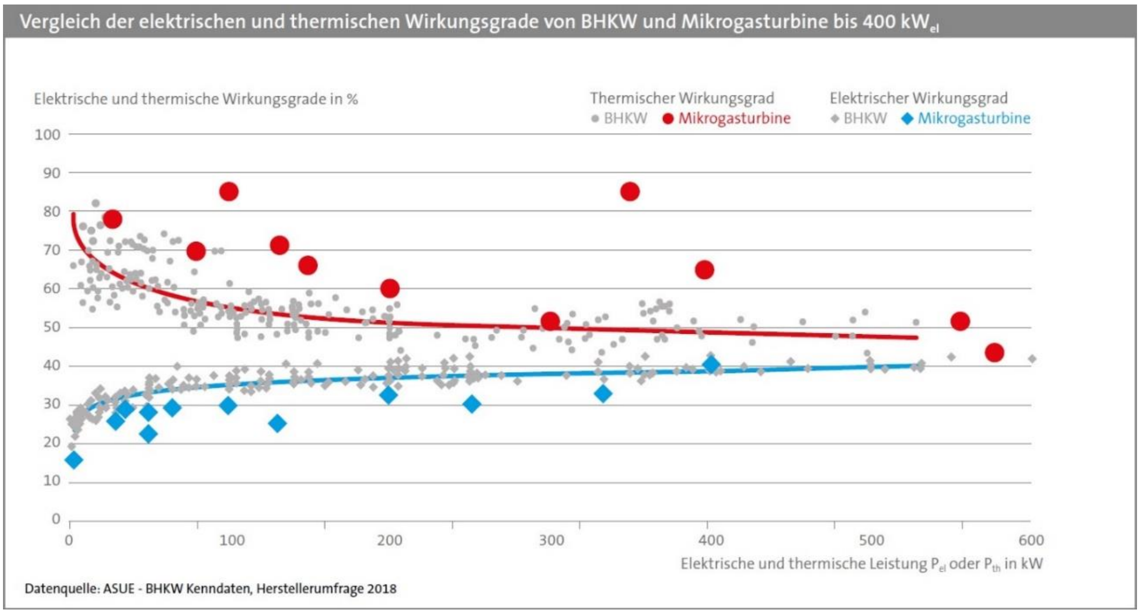

Figure 42: Comparison of total, electric and thermal efficiency of CHP and micro gas turbines depending on installed electrical capacity; © ASUE 2018.

The efficiency of a CHP unit is depending highly on the 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 measurements of gas engines. The red line shows the average thermal efficiency. The blue line the electric efficiency. Red and blue dots are from measurements of micro turbines.

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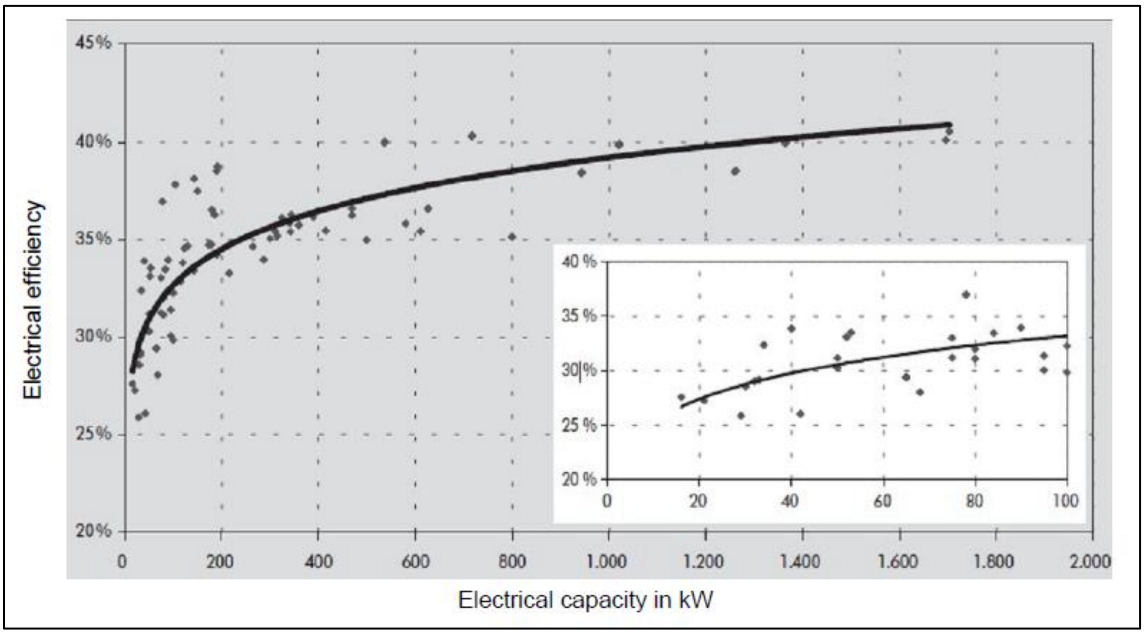

Figure 43: Electric efficiency of various CHP´s; © Biogas guide book 2019.

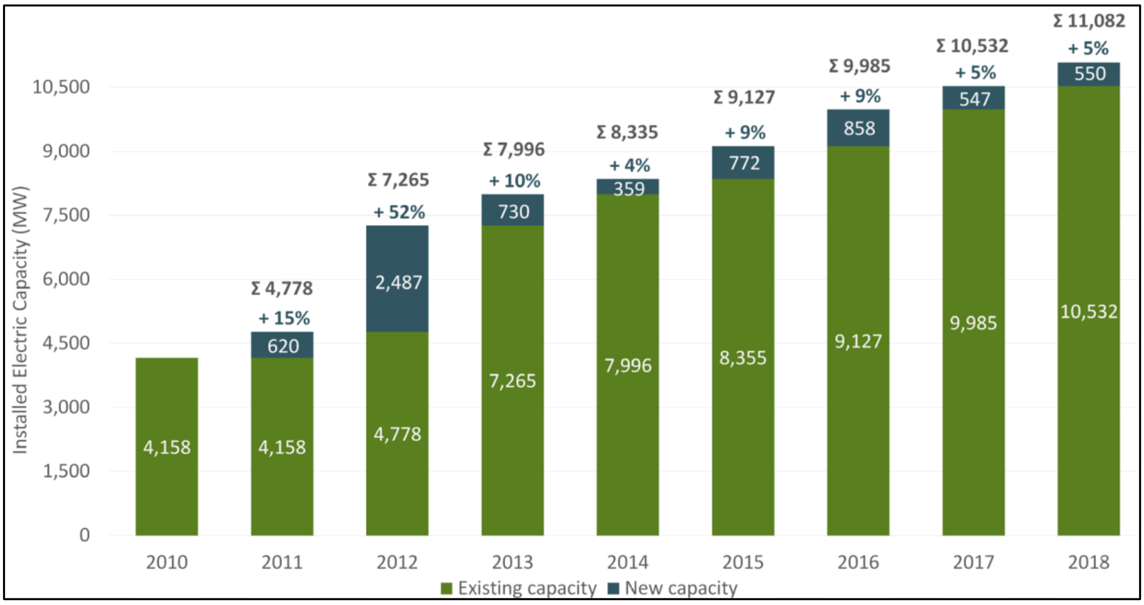

Figure 44: Development of installed electric capacity of biogas plants in Europe expressed in $MW_{el.}$; © EBA 2020.

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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 Boiler/Cooking

In some cases, the direct heat utilization is an option for biogas. Within Europe, this is not applied very often because electricity has a much higher value and can be used more flexibly than heat.

However, if heat can be used, this is mainly done to produce process heat in the industry, steam, peak load and failure reserve heat for district heating systems. If the district heating system is managed by a biogas plant, the base load for the heat supply mainly comes from the CHP unit of the biogas plant.

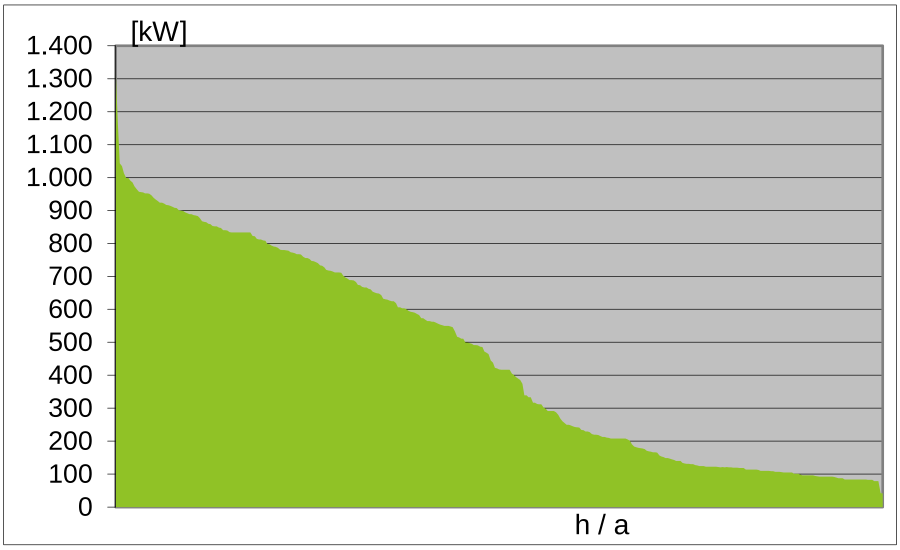

Figure 45: Typical heat demand curve in a local district heating system © AKBOE 2012.

Figure 46 shows that the heat demand usually varies greatly throughout the year. Peak loads (left) are only needed for some hours per year, while the base load is almost always needed.

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

10.4 Upgrading biogas to biomethane quality

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

Upgrading units purify the biogas typically up to 90-99% methane content, fulfilling the requirements of natural gas. This offers an additional wide range of applications like:

- Direct use as transport fuel
- Gas grid injection and following applications
    - Transportation
    - Heating & cooking
    - Combined heat & power

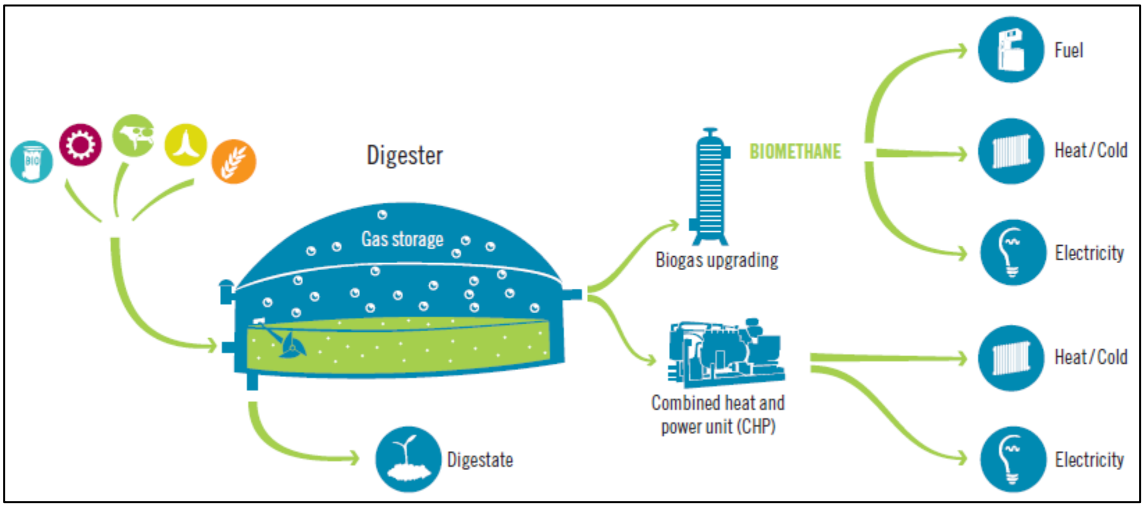

Figure 46: Process of biogas production and its possible applications; © Fachverband Biogas 2017.

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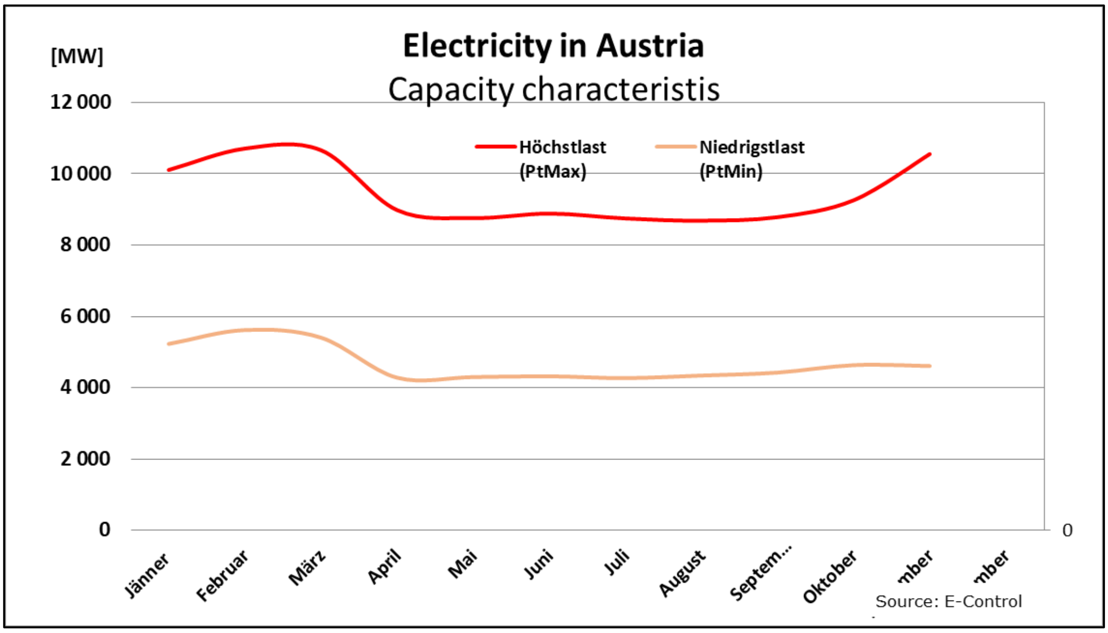
In Europe, two main grids for transportation of energy are available, the electricity and the gas grid. Both grids play a key role in delivering energy to consumers, for the security of supply and both have their own specifications. These characteristics will be explained based on data from Austria. In 2018 energy demand delivered through the gas grid reached 90.7 TWh compared to the electricity grid with 66.4 TWh. While the electricity grid reaches a peak load of around 11 $GW_{el.}$ the gas grid exceeds this value nearly threefold to around 28 GW_{th}. At least due to its topographic conditions Austria has a very high amount of installed hydro pump storage with a total storage capacity of 3.3 $TWh_{el.}$ and with a max. performance of 6.4 GW_{el}. In comparison the Austrian gas system has a cavern storage capacity of 91.8 $TWh_{th.}$ in total and a performance of 44.6 GW_{th} (E Control 2019). For the latter, the most important point is probably not only the max. storage capacity but also the possible maximum performance at times where the demand is usually very high, and the actual stored energy is at its lowest point. These points usually happen in the first two months of the year where low temperatures cause high energy demand and on the other side hydro power from river runs off and wind and PV are sometimes at the lowest level. Figure 48: Maximum available capacity of pump hydro storage compared to gas storage within caverns per week; © ENTSO E, E-Control shows these points for both grids. While pump hydro storage can secure security of supply for about 3 days, the gas storage systems allow to secure supply for more than 20 days. These figures bring new facts to light and highlight the importance of the gas grid.



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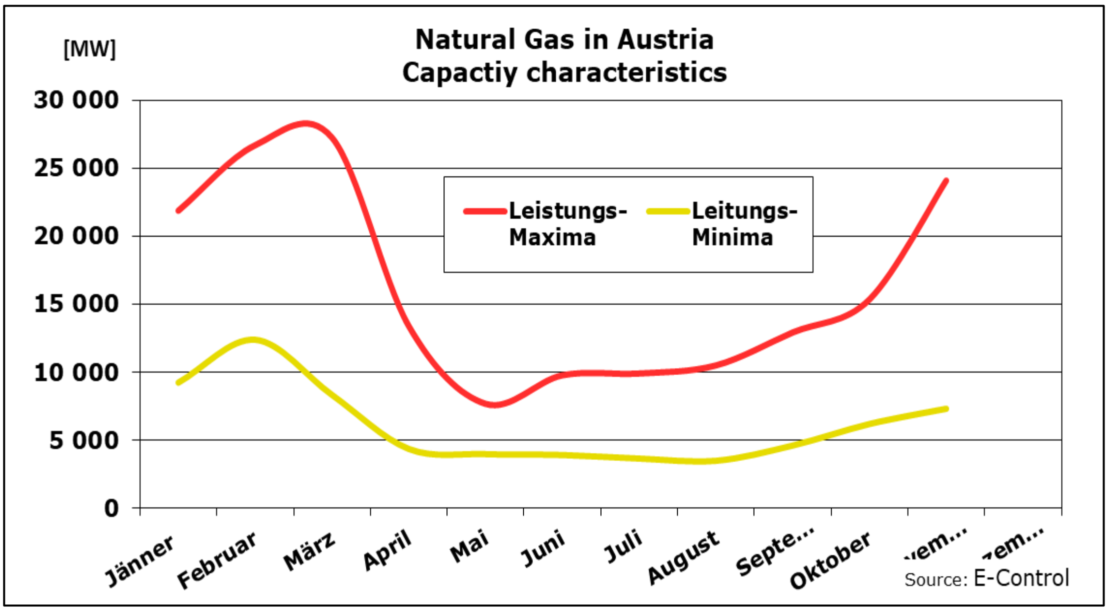
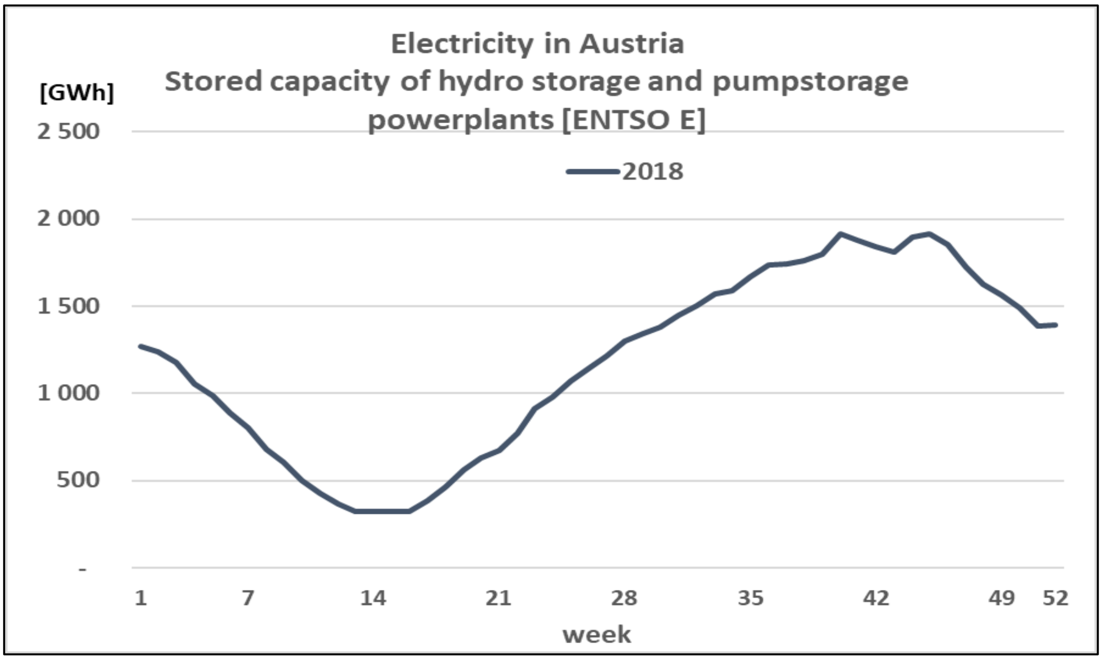


Figure 47: Maximum and minimum load of Austrian electricity grid compared to the gas grid; © E Contro 2018



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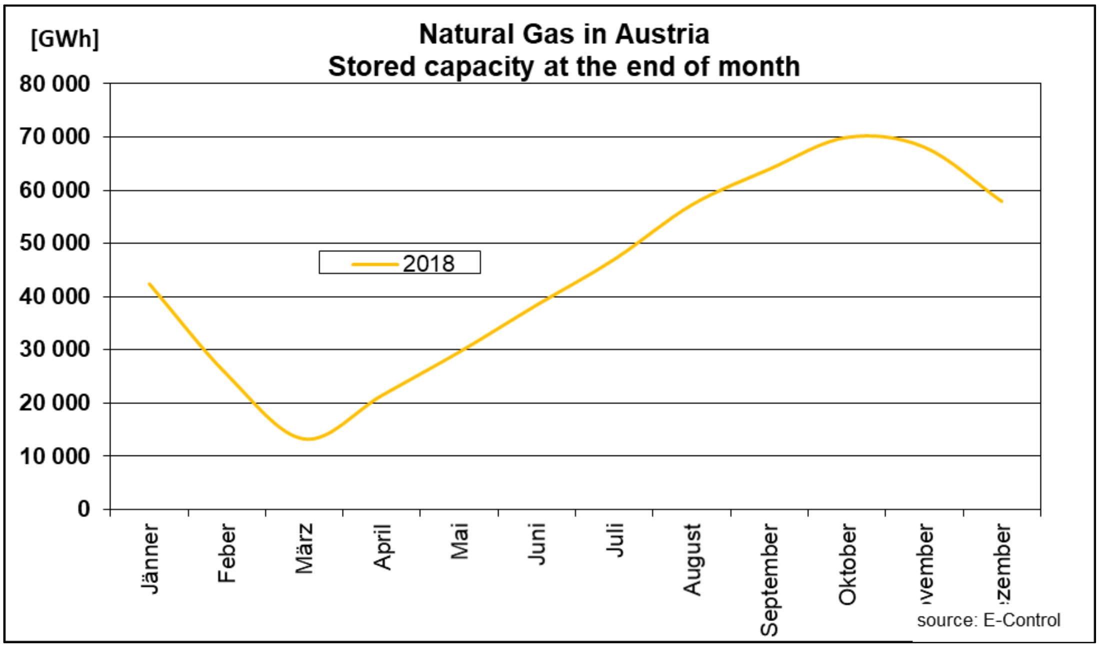

Figure 48: Maximum available capacity of pump hydro storage compared to gas storage within caverns per week; © ENTSO E, E-Control 2018

Natural gas is a fossil fuel. If it is burned, additional GHG is released. In the light of the Paris Agreement, also the gas grids need to switch to renewable energy. The predominant and most promising technique to achieve this is upgrading biogas to biomethane.

Before biogas can be injected into the gas grid, biogas needs to be purified from possible components which are not allowed to be injected into the gas grid. These components are mainly the water content, several components of Sulfur and Nitrogen, Oxygen and at least Siloxane etc. Additionally, the required caloric value and Wobbe Index need to be adjusted through elimination of carbon dioxide. Table 22 shows typical components within biogas and the requirements for gas grid injection.

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

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}

Due to their components and density, different gases have a different flow speed, caloric value etc. and therefore different properties. For gas devices the Wobbe Index is, besides the caloric value of the gas, an important characteristic quantity. It expresses the convertibility of different gases so that those can be applied with the same gas burner without changing the burner nozzle. The Wobbe Index is calculated by dividing the higher heating value with the radical of the relative density between gas and air:

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

Therefore, each burning device has the *Wobbe* Index included on its labelling.

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

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**

10.4.1 Purification

Purification of biogas usually includes desulphurization, drying and separation of carbon dioxide.

10.4.1.1 Desulphurisation

The content of hydrogen sulfide within the biogas depends on the used feedstock. Hydrogen sulfide itself has corrosive properties. Additionally, it will be converted through combustion to sulfide dioxide which accumulates on sensitive components and is an environmental pollutant causing acid rainfall. Usually H_2S occurs in biogas at a higher concentration than the upper limit value for gas grid injection. Therefore, it must be reduced. As oxygen, different components of nitrogen and sulfur are limited within biomethane and additionally would lower the caloric value and the Wobbe Index, desulphurization differs between direct CHP application and upgrading to biomethane. Instead of using air for biological desulphurization (air contains mainly nitrogen which should not be present in pure biomethane), pure oxygen is used. Additionally, desulphurisation is in most cases done in more than one step. It is often a combination of several steps from the following possibilities:

- Chemically by adding doses of iron salts into the liquid phase of the digester
- Biological desulphurisation with oxygen in an external column
- Adsorption on activated carbon

10.4.1.2 Drying

At its formation, biogas is saturated with water vapor and reaches the dew point at each point it is cooled, and water will occur. The appearance of water within the gas grid needs to be avoided because it could be accumulated at the lowest point of the gas grid and cause pressure variation. Additionally, it could cause damage to application devices like an internal combustion engine. Different dewatering techniques are used to fulfill the requirements like:

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- Condensation through cooling
- Adsorption with zeolites, silica gels or aluminum oxide
- Absorption with glycol

The most common technique for dewatering the biogas is cooling with a cooling aggregate. Additionally, the carbon dioxide removal step like pressure swing adsorption also removes water. This can be considered as a security step. Adsorption with zeolites, silica gel or aluminum oxide is done in two alternately pressure vessels.

10.4.1.3 Carbon dioxide removal

Carbon dioxide removal is the necessary step to reach the minimum level of caloric value and Wobbe Index for gas grid injection. Choosing the right technique depends on several parameters such as the required methane content, energy demand, required gas grid pressure, 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

10.4.1.3.1 Pressure Swing Adsorption (PSA)

Pressure swing adsorption is a proven method of separation and has been applied for decades. It is used in the gas industry, and was adapted to the requirements of 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 excellent characteristics such as a large surface area and a certain pore size. Usually at least two columns work directly together. To reach a continous process always at least 4 up to 8 columns are installed in a PSA device.

When biogas is fed into the first PSA column, the activated carbon physically adsorbes CO_2 while methane passes the process. The moment the activated carbon has reached full load with carbon dioxid the raw biogas inlet will be closed and led to another parallelly installed vessel also filled with activated carbon. Removing carbon dioxide from the acitivated carbon is done by directing the gaseous content to another gaseous empty vessel with activated carbon until both vessels have reached nearly the same pressure. The last step of emptying the carbon dioxid loaded vessels is done with a vacuum and the vessel is again ready for removing carbon dioxide from raw biogas. These connected steps are necessary to reach high contents of methane in the purified biomethane, to guarantee low methane losses and to avoid unwanted high energy demand. Therefore, at least four vessels are involved to reach a continous process. A positive effect of the process is that the remaining and unwanted gases like H_2S are also kept by activated carbon and it finally dries the gas. At the moment H_2S passes the process, the activated carbon needs to be maintained or changed. In order to avoid that the lifetime of the activated carbon is too low, fine-cleaning must be carried out to remove the H_2S before the biogas is pumped into the adsorption column.

The methane losses are mainly dependent on the design of the system. The CH_4 in the exhaust gas must be burnt because of its greenhouse gas relevance.

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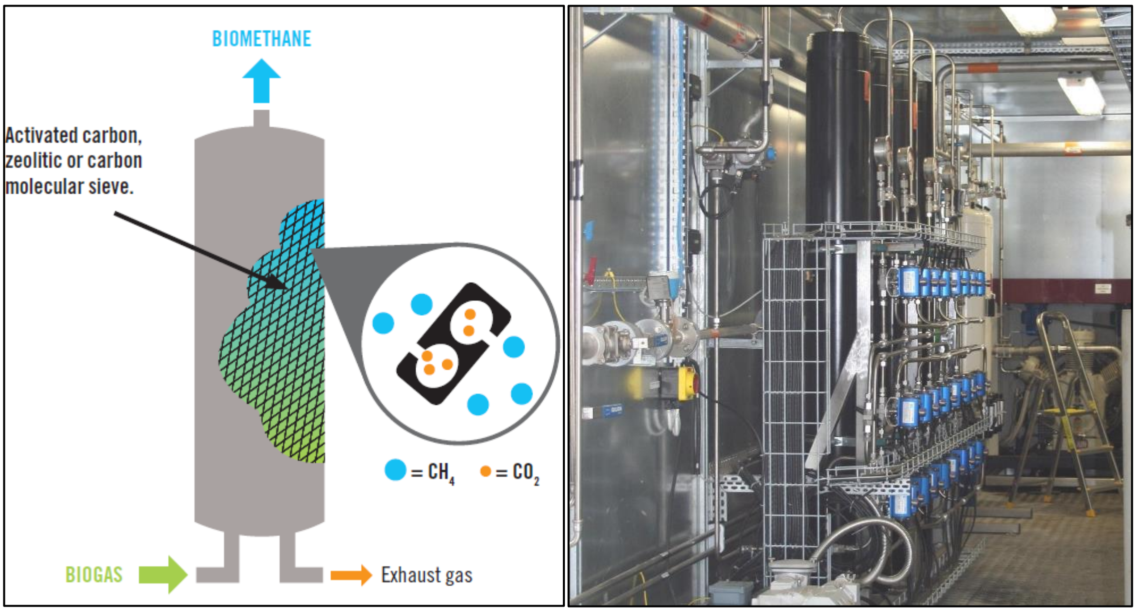

Figure 49: Left: Detail of a CO_2 separation vessel with activated carbon in a Pressure Swing Adsorption device (PSA); © Fachverband Biogas 2017, right: PSA column.

10.4.1.3.2 Water scrubbing

We all know this effect in our sparkling beverages: in the cold and under light pressure carbon dioxide is soluble within the fluid. By releasing pressure, for example by opening the beverage bottle, carbon dioxide is released. Heating the fluid up lowers the solubility of carbon dioxide additionally. Water scrubbing uses this well-known effect of different solubility of carbon dioxide and methane within water. In a first step biogas is cleaned from water droplets and other bigger impurities, then flows pressurized with 4 up to 10 bars into the scrubber column at the bottom while in counterflow cold water flows from top to bottom. Carbon dioxide, hydrogen Sulphur, ammonia and particulates are dissolved in the water and at the top of the column methane rich biomethane can be extracted. For gas grid injection the biomethane again needs to be dried. At the bottom of the column carbon dioxide rich water with low content of methane is led to the flashing tower. In order to keep the dissolved methane within the process the pressure is removed as a first step, and dissolved methane escapes from the water and is directed into the process again. In a second step the exhaust gas rich water is directed into the flashing tower where in counterflow the CO_2 etc. is released into the air by lowering the pressure to ambient air pressure and air is pressed inside from the bottom. If the hydrogen Sulphur content is not too high within biogas and because H_2S dissolves very well in water, water scrubbing usually reaches the requirements for the upper limit value of H_2S for a gas grid injection without any further treatment. Depending on the methane content in the exhaust gas an additional post-combustion step is needed.

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

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

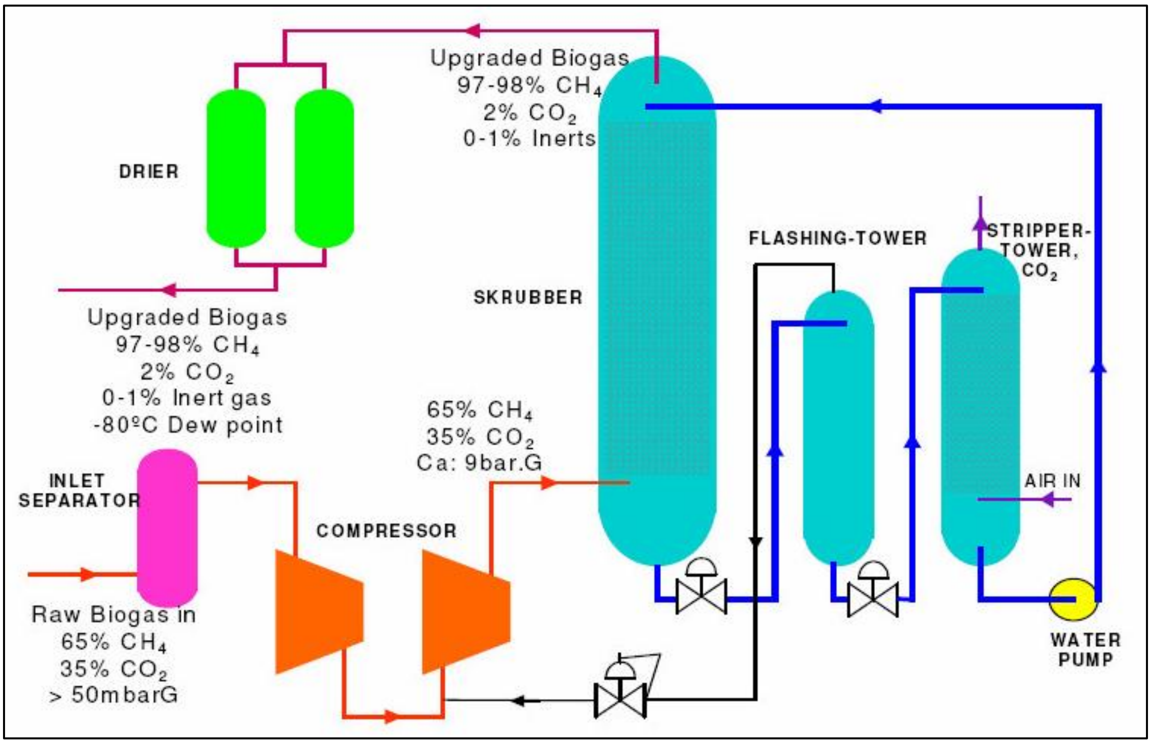

Figure 50: Scheme of water scrubbing technique; © Tretter H. 2003.

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

10.4.1.3.3 Physical scrubbing

Carbon dioxide removal through physical scrubbing is also based on the different solubility of gases within fluids. The process is very similar to water scrubbing with the main difference of the solvent. Using a special solvent, Polyethylene glycol (brand: Selexol) has the advantage of a higher solubility of gases like CO_2. Therefore, for this process less pressure and smaller columns are needed for the same performance compared to water scrubber. The downside is that it is more difficult to regenerate the solvent. Usually heat is needed to separate CO_2 from the solvent after the scrubbing process.

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

10.4.1.3.4 Chemical Scrubbing

Chemical scrubbing is similar to the process of physical scrubbing. The main difference between physical scrubbing and chemical scrubbing technologies is that for the latter the affinity to CO_2 is even higher. The consequence is a very high selectivity of the process. The purity of the gases is very high, e.g. above 99.9% methane concentration and less than 0.5% methane losses are possible. Another advantage is that the scrubbing columns can be operated at atmospheric pressure, while all other biogas upgrading technologies are operated with pressurized columns. The disadvantage is that the recovery of the detergent needs to be done with heat. For the latter it is good to have exhaust heat nearby. Used chemicals are Monoethanolamine (MEA), methyldiethanolamine (DEA) etc.

10.4.1.3.5 Membrane technique

Membrane technique uses the different permeability and size of various gaseous molecules to differ through special conditioned membranes. The permeability of membranes for CO_2 is 20 times higher than the one for CH_4. The hollow fibres itself are bundled together in a steel column. Depending on the needed performance several columns work in parallel.

To reach a high methane content in the produced gas and to avoid an excessive loss of methane within the exhaust gas, the membrane technique is usually applied in a two or three stage process. As nitrogen does not diffuse through the membrane wall either and stays in the produced gas together with the methane, it is important to avoid any accumulation of nitrogen within the biogas. To avoid damaging the membranes too quickly, biogas needs to be dewatered, de-oiled and desulfurised very well before entering the membranes.

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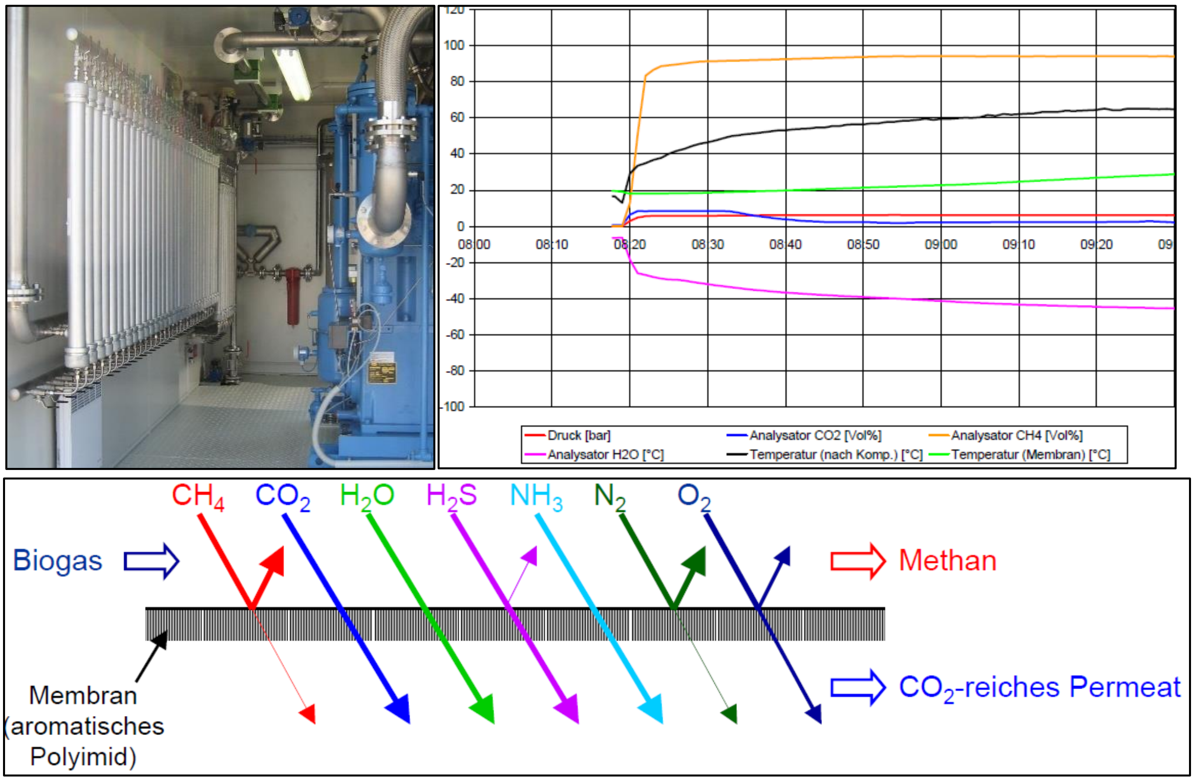

Figure 51: Top left: CO_2 separation through membrane technique, top right: ramp up curve after start, bottom scheme of membrane technique; © top right & bottom: © Harasek, 2009.

The choice of upgrading technique depends on several factors such as:

- Plant size
- Required pressure after purification
- Upper limit of methane content in the off gas
- Availability of waste heat
- Availability of wastewater
- Availability of maintenance companies

During the last two decades, upgrading techniques underwent huge developments and the installed techniques changed according to special conditions and the regional situation of the biogas plant but also based on the technical development and legal requirements. About 500 industrial installations are upgrading biogas to biomethane today. Many experiences with this technology have been gained throughout the last 20 years. Thus, we can conclude that upgrading biogas is the state-of-the-art and an approved technology.

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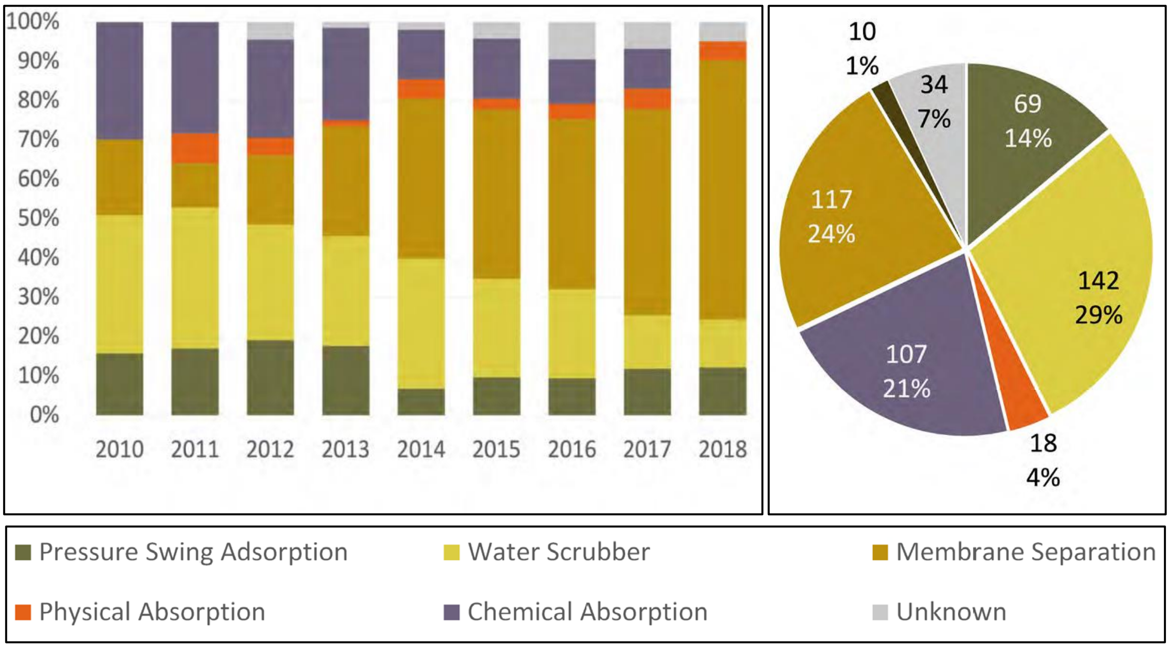

Figure 52: Relative use of upgrading techniques, left: worldwide, right: Europe; © EBA, DMT 2020.

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11 Special Case: Household Biogas Systems

Biogas systems can be built at nearly any size. The volume of the digester can be constructed in a range from below 1 m^3 until several thousand m^3. Biogas technology at a larger scale, often referred to as industrial or commercial size, is described in the chapters above. This chapter is about small-scale biogas, sometimes called domestic biogas, home digesters or household biogas systems.

Counting the amount of installed biogas plants in the world, small scale digesters are by far the most frequently installed ones worldwide.

There are several definitions of household biogas systems. The probably most acknowledged definition is the one developed by the International Organization for Standardization. ISO 20675 gives the following definition:

"Household scale Biogas system: Biogas system with a production capacity of biogas having an energy content of 1 MWh – 100 MWh per year". Which equals about 11 kW_{th} full load capacity.

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

11.1 Occurrence

There is no reliable source of the number of installed household biogas systems worldwide and only very rough estimations were published by several sources.

In China, an estimated total of 40 million domestic systems were installed. 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 regarding domestic biogas installations[4]. Also, in Latin America around several thousand small biogas plants for rural households are in operation.

11.2 Reasons for household biogas systems

There are many reasons to support and install household biogas systems, some of them are:

- **Own energy production**. In huge areas of the world, energy supply is still a challenge. Energy costs money, time and causes GHG emissions (see points below). Producing own renewable energy, e.g. for cooking or lighting, through a domestic biogas plant helps people to become independent from buying or collecting fuels.

[3] Source, Indian Biogas Association

[4] The main source for this paragraph is "Biowaste to Biogas", published by Fachverand Biogas 2019. Additionally, several expert opinions and experiences from The German Biogas Association are included.

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- **Energy production saves money**. Many people need to spend a substantial amount of their money for 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 are depending on firewood, mainly to cook their meals. The forests in those areas are often not managed in a sustainable way. People cut down more trees than annual growth. The consequence is deforestation. Household biogas systems can be a part of the solution because the people with need of cooking energy can then produce fuel by themselves. Thus, the need to cut down trees is reduced.
- **Health**. Inner space cooking on open fireplaces with firewood causes high emissions of smoke, soot and particles. The inhalation of those gases and particles causes diseases, such as lung diseases and eye inflammation. Biogas is burned with much lower emissions. Hence, preparing meals with biogas has a positive effect on health.
- **Due to an already existing lack of firewood, people often burn dried cow dung**. The higher ammonia emissions also cause eye inflammation and bring a loss of nutrients into the air (mainly nitrogen).
- **Time saving**. Collecting firewood often takes a substantial amount of time for woman and children. By using feedstock, which is usually available close to the house, and digesting it to biogas, much time can be saved.
- **Greenhouse Gas Emission (GHG) reduction**. The production of biogas and its use as fuel has several positive effects on GHG emissions:
    - By replacement of fossil fuels, CO_2 emissions are avoided.
    - By avoiding deforestation in regions where forests are not used sustainably, the CO_2 emissions that occur by deforestation, are not released.
    - Stored organic material (for example landfilled kitchen wastes or animal excrements) emit methane. By processing it in a gas tight biogas system and burning the biogas, GHG emissions can be avoided.
    - However, the GHG emission reduction depends much on the gas tightness of the household gas system. The produced biogas consists mainly of methane which has a very high GHG potential. Thus, if a digester is not gas tight, the biogas plant can cause an environmental damage. That´s why the household biogas system must be as gas tight as possible![5]
- **Fertiliser**. (Nearly) all nutrients that are fed into the system with the feedstock will remain in the digestate and are used for fertilizing plants. Additionally, organic bound nutrients are mineralized during digestion and by that, plants can assimilate them much better. Thus, the digestate is a very valuable fertilizer. It is often reported that fertilizing the fields with the digestate leads to improved harvest yields (Gilbert, J. 2019 and Wilken, D. (2018).
- **Sanitisation**. Usually many kinds of bacteria are reduced when being processed in a biogas system, especially potential pathogen germs. The reason is that the bacteria inside the system are optimally adapted to the growing conditions inside a digester and the feedstock, whereas potential pathogen bacteria are not and thus cannot compete with the (non-pathogen) bacteria. Many studies show this sanitization effect (Fachverband Biogas, Hintergrundpapier Hygiene, 2019). Only some kind of feedstock categories might cause problems, e.g. meat products or slaughterhouse wastes, which need to be sanitized and therefore should not be used as feedstock in domestic biogas plants without sanitization step. All vegetarian feedstocks can be used in a biogas digester without risks of pathogen bacteria. In some cases, human excrements are digested. Again, this has a sanitation effect by reducing (potential pathogen) bacteria.
- **Weed control**. There are usually many viable weed seeds in animal manure or dung. If the farmer is fertilizing her/his fields with (not digested) manure, many seeds are

[5] This effect is true for all biogas plants. Industrial and household biogas systems.

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spread upon the fields again. Usually the farmer spends many hours or pesticides for 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 whole household biogas installation consists mainly of a digester tank with an inlet for the feedstock and an outlet for the produced 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 on the upper part of the digester. Sometimes an external balloon serves as gas storage. From the gas storage, a hose is leading the produced 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. Typically, as installed in warmer climates household biogas plants are not equipped with a heating or stirring system (with only few exceptions). In colder climates, some systems are surrounded by a simple green house. The mechanical parts (if there are some at all) 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 some kilograms. The used feedstocks are animal excrements, residues from harvests (e.g. not sellable fruits or leaves of plants) or food wastes, especially if it is vegetarian. Food waste containing meat might cause 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). Wastes that might be contaminated with pathogen bacteria (like slaughterhouse waste) should not be used, because domestic biogas plants do not have a sanitization unit.

The produced amount of biogas is low (some m^3 per day). The digester volume is usually just some m^3 and can go up to 45 m^3. 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, experiences show that local knowledge and clear responsibilities are key for a 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 and because as the majority of household biogas systems in the world are installed in China, the 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 inside. As gas is produced, the liquid is displaced into a compensation tank and gas pressure

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increases with 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 (releasing methane emissions!) and resistance to corrosion is questionable. Especially in a long-term operation the material often corrodes (H_2S and water turn into sulphurous acid) and cracks can occur. If there are gas leakages, the GHG balance is questionable and, in some cases, those installations are producing an environmental damage[6]. Thus, it must be controlled constantly during operation that there are no cracks in the digester wall.

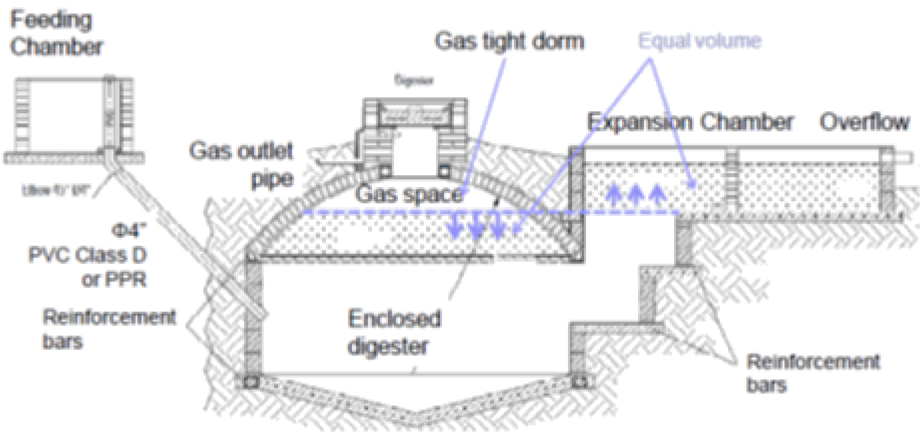

Figure 53: Fixed dome digester. Source: Akut Umweltschutz

11.5.1 Floating drum digesters

Floating-drum plants consist of an underground **digester** (cylindrical or dome-shaped) and a moving gas-holder. Depending on the amount of gas stored in the gas drum, it moves up and down with the gas fluctuation - thus the floating drum indicates the amount of gas stored. In order to increase the gas pressure, stones are often placed on top of the inner drum. These types of digesters are popular in India.

[6] This is valid for all biogas systems, household and industrial plants.

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

The picture 72 shows the two black drums. The white tube in the foreground is the outlet constructed as overflow. If, for example, 1 litre feedstock is fed, 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 is evaporating and fertiliser (in a consistence similar to soil) is remaining.

There is a generally negative aspect of floating drum digesters: the gap between the inner and the outer drum through which methane emissions can occur (see Picture 73).Therefore the gap should be as small as possible but wide enough to let the inner tube float up and down.

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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 (special membranes like EPDM). The bag serves as digester, holding the liquid, and in some constructions as gas holder in the upper part. Other systems use a gas storage in form of an external balloon. Usually plastic bag digesters are not equipped with a heating system or mixers. However, there is a system with a simple stirring system available, see Picture 74. Feedstock is fed into a plastic bag where the biogas is produced. There are several advantages of the system: it is relatively robust, gas and liquid tight, and the material is resistant to corrosion.

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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 a very popular method in developing countries where people often have to spend hours each day collecting firewood for cooking or where other sources for energy, e.g. 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 sources of fossil gas fuels like diesel, kerosene or LPG (United States Environmental Protection Agency, 2008). Furthermore, the biogas can also be used directly in a gas lantern and provide a steady source of lighting.

Due to the low energy output, household biogas systems are seldomly used for electricity production.

11.7 Situation in Europe

Typically, European biogas manufactures deal only with biogas systems at larger scale. In Europe there are (almost) no official installations. Only some digesters are operating at private level, due to several reasons:

The obligations to get an approval/permit are defined very differently in Europe. There are huge differences on state, country and even local level. In some countries those systems are not defined, or the obligations are not clear. Usually such an approval requires the compliance with several standards, which are not met easily, 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 application of the digestate and several other aspects.

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European households are usually well connected to the energy system (electricity, gas and/or heat). Thus, there is only a small need for energy self-sufficiency, although several people are in principle interested in that aspect.

At least in Northern Europe and areas where the wintertime is cold, household systems might not work well without a heating system, which is usually not installed.

A household biogas system can be installed with low costs, which is one essential advantage in developing countries. However, the amount of energy produced is low as well.

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