Overview and Categorization of European Biogas Technologies

- Introduction: Anaerobic Digestion -

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DiBiCoo – Digital Global Biogas Cooperation
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Executive Summary of D2.2

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. In order to incorporate more relevant technologies and Biogas applications, some sections already outlined in this technology overview (e.g. on various pumps, pipes and valve types; or safety equipment) will be presented in an updated version later in October 2020.

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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List of Abbreviations

AD	Anaerobic Digestion
CHP	Combined Heat & Power
D	Deliverable
d	day
HRT	Hydraulic retention time [d]
OLR	Organic loading rate [kg_{VS} m^{-3} d^{-1}]
T	Task
SC	Steering Committee
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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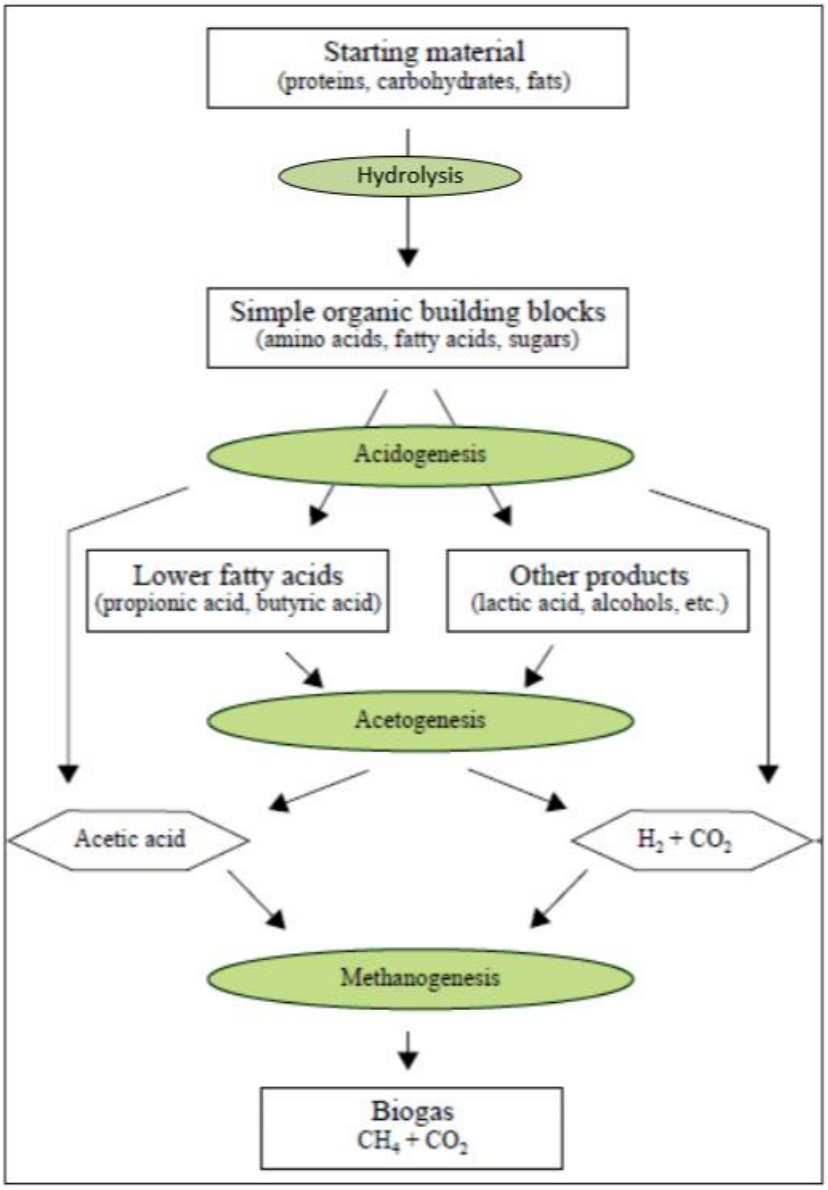

Figure 1: Scheme of the decomposing process of organic matter within AD; © FNR 2012

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

Figure **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 do 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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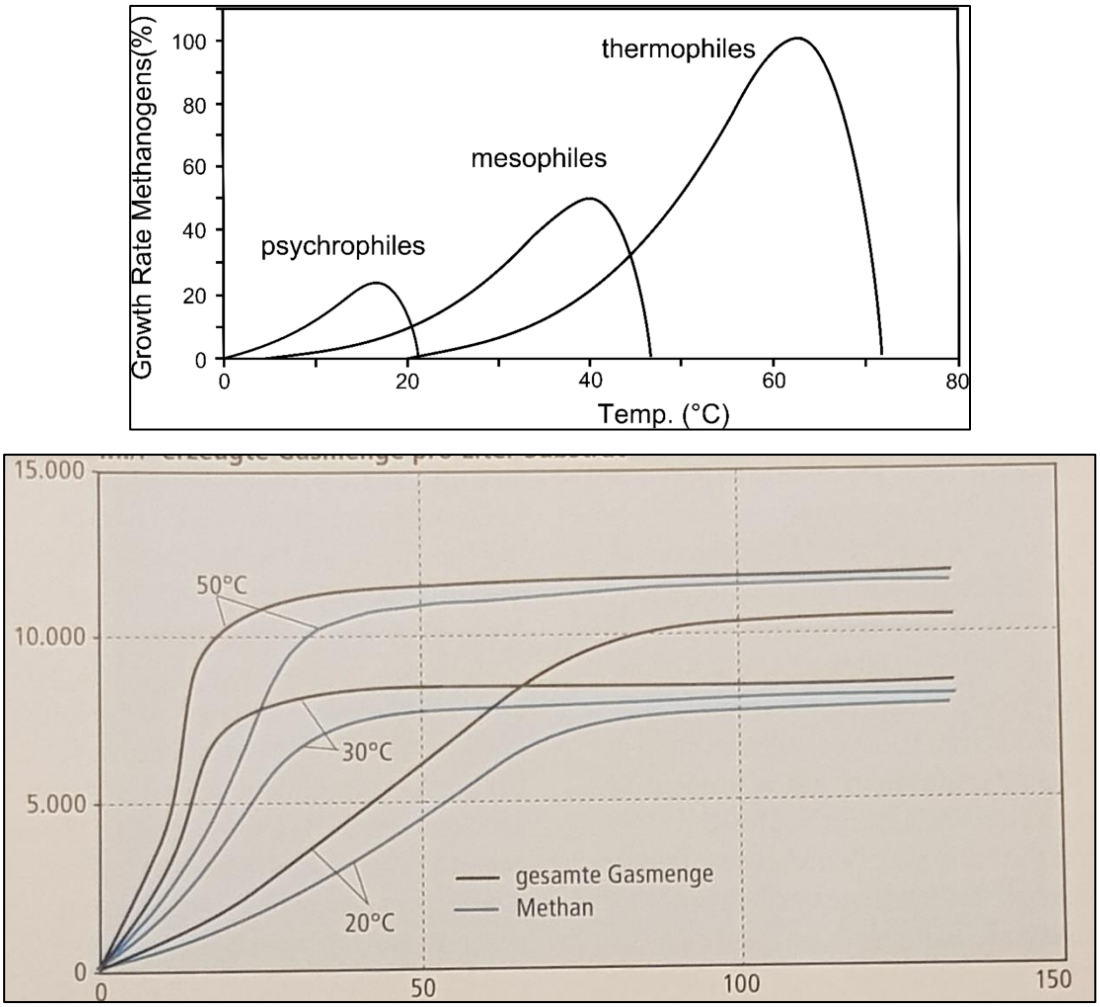

Figure 2: Growth rate of methanogenic bacteria at different temperature profiles and biogas (ml l^{-1}) forming potential depending on temperature and retention time (days); © Baader, Schulz 2006, 1978, Van Lier 1997

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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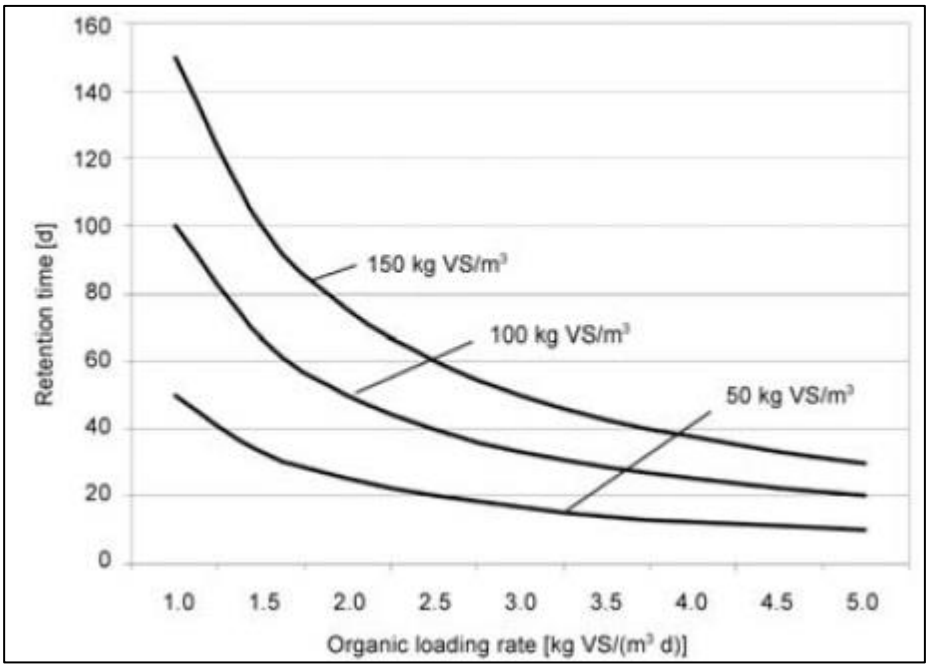

Figure 3: Correlation between organic load rate (OLR) and hydraulic retention time (HRT) depending on volatile solid content of feedstock; © Paterson 2012.

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.

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

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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.

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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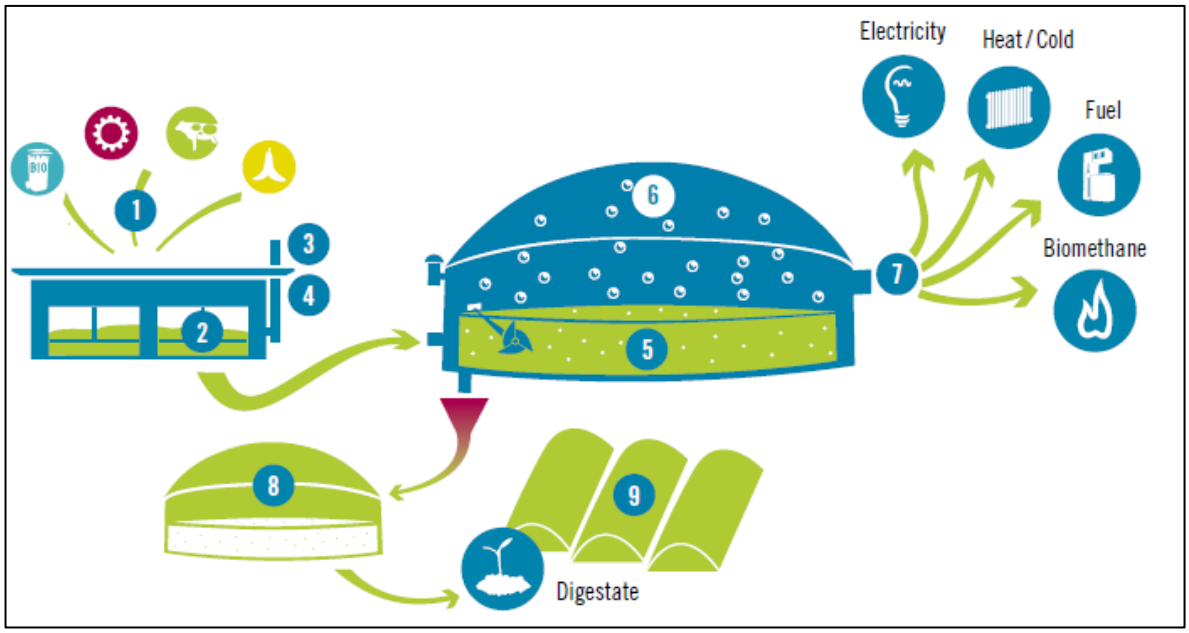

Figure 4: Scheme of a biogas plant 1: different types of feedstock, 2 storage of feedstock, 3+4: air collection and treatment, 5: digester, 6: biogas storage, 7: biogas application, 8+9: digestate storage; © FVB, 2009

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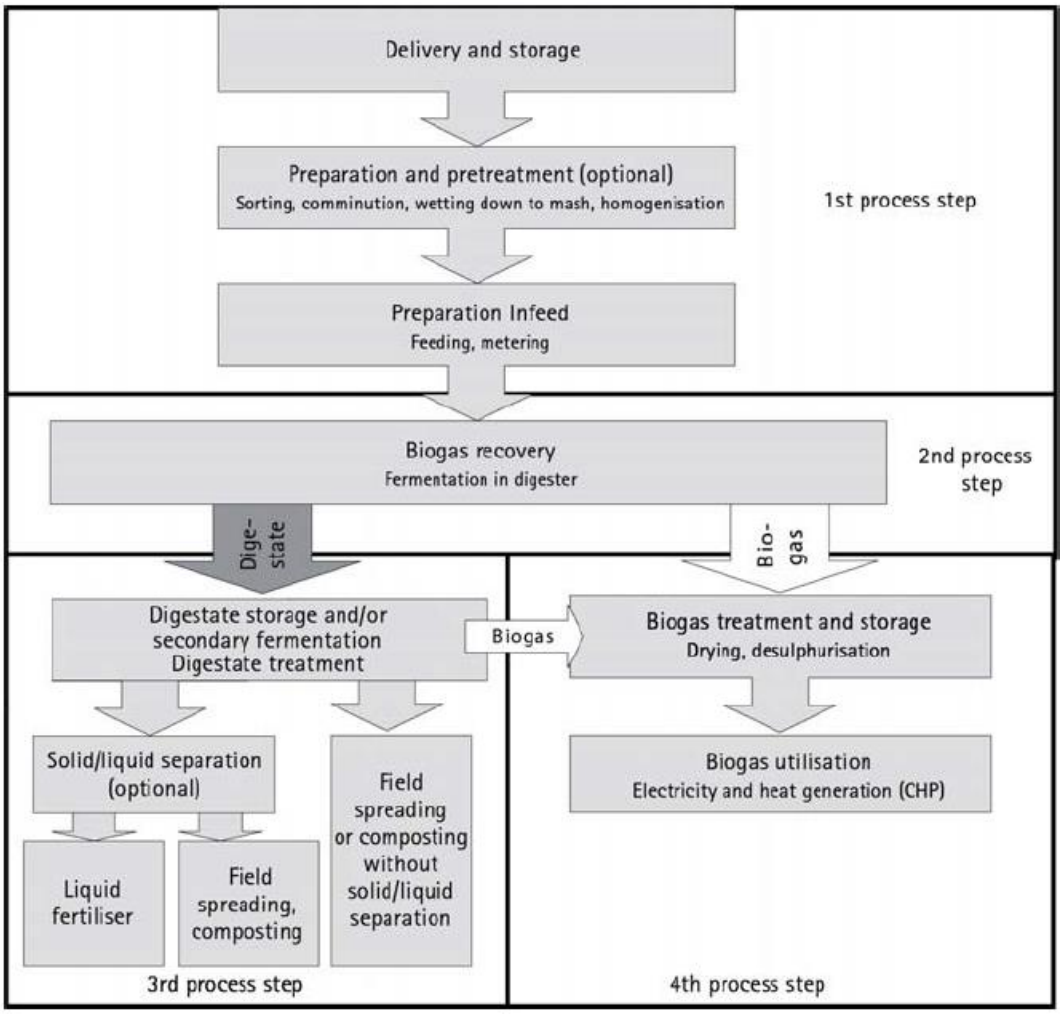

Figure 5: Usual process step of biogas plants; © Paterson, 2012

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Digital global Biogas Cooperation

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