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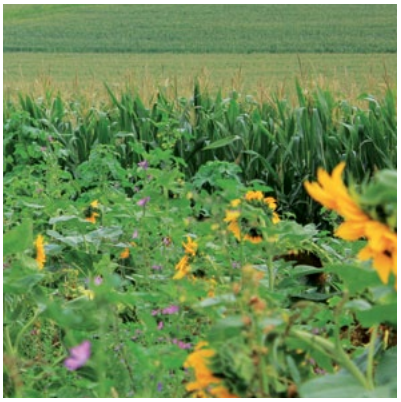
Guide to Biogas

From production to use



GUIDE TO BIOGAS FROM PRODUCTION TO USE

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Deutsche Gesellschaft für
Internationale Zusammenarbeit

Dag-Hammarskjöld-Weg 1-5
65760 Eschborn
Germany

T +49 6196 79-4102
F +49 6196 79-115
E energy@giz.de
I www.giz.de

biogasportal.info

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Internet: www.dbfz.de

Partners: **Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V. (KTBL)**
Internet: www.ktbl.de

Johann Heinrich von Thünen-Institut (vTI)
Internet: www.vti.bund.de/de/institute/ab/

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List of contributors

Name	Institution
Thomas Amon	University of Natural Resources and Life Sciences, Vienna (BOKU)
Hartwig von Bredow	Schnutenhaus & Kollegen (law firm)
Jaqueline Daniel-Gromke	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Helmut Döhler	Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Elmar Fischer	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Erik Fischer	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Jörg Friehe	Johann Heinrich von Thünen Institute (vTI)
Henrik Gattermann	Formerly: Institut für Energetik und Umwelt gGmbH (IE)
Sven Grebe	Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Johan Grope	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Stefan Hartmann	Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Peter Jäger	Formerly: Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Uwe Jung	Formerly: Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Martin Kaltschmitt	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Ulrich Keymer	Bavarian State Research Centre for Agriculture (LfL)
Susanne Klages	Formerly: Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Jan Liebetrau	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Anke Niebaum	Formerly: Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Jan Postel	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Gerd Reinhold	Thüringer Landesanstalt für Landwirtschaft (TLL)
Ursula Roth	Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Alexander Schattauer	Formerly: Johann Heinrich von Thünen Institute (vTI)
Anne Scheuermann	Formerly: Institut für Energetik und Umwelt gGmbH (IE)
Frank Scholwin	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Andre Schreiber	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Britt Schumacher	Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Markus Schwab	Formerly: Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Ralf Stephany	PARTA Buchstelle für Landwirtschaft und Gartenbau GmbH
Thomas Weidele	Formerly: Institut für Energetik und Umwelt gGmbH (IE)
Peter Weiland	Johann Heinrich von Thünen Institute (vTI)
Marco Weithäuser	Formerly: Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Ronny Wilfert	Formerly: Institut für Energetik und Umwelt gGmbH (IE)
Bernd Wirth	Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Sebastian Wulf	Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)

The addresses of the institutions are given on page 229.

Purpose of the Guide

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Against the backdrop of the continuing climb in global energy prices, energy recovery from organic residues and waste streams is becoming an ever more attractive proposition. Alongside the generation of storable renewable energy, the distributed production of biogas can help not only to develop rural regions but also to strengthen small and medium-sized enterprises.Thanks to the positive statutory framework for renewable energy sources that has existed in Germany since 2000,the production and utilisation of biogas has rapidly expandedin recent years. In 2010, there were already over 5,900 biogas plants in existence, the majority of which are operated in an agricultural setting. Over the same period, there have also been significant changes and improvements in the technologies used. Germany's wealth of experience in biogas technology is nowincreasingly in demandat an international level.

The purpose of this Guide, therefore, is to make a contribution to giving exhaustiveand real-world-based answers to technical, organisational, legal and economic questions in relation to agricultural biogas generation and utilisation.

The present document, which was developed by the Agency for Renewable Resources (Fachagentur Nachwachsende Rohstoffe e.V. – FNR), thus provides the reader with a valuable reference work,in which selected authorscontributeinformation on the subjects of biogas technology, capital expenditure planning and plant operation. To cater for an international readership, the Guide has been adapted and translated in connection with the biogas projects implemented by the Gesellschaft für Internationale Zusammenarbeit (GIZ) and funded by the German Federal Ministry for Economic Cooperation and Development (BMZ). It presents the state of the art in biogas technology for efficient generation of power, heat, cold and/or gas andaffords the user access to the information required for making authoritative and context-sensitive decisions on the topic of biogas. This Guide, therefore, not so much describes a standardised technology, but rather demonstrates ways in which an adapted technology can be planned and selected to meet the needs of a specific context.

1.1 Objective

The growth in energy generation from biogas in Germany is attributable in the main to the existing administrative framework, above all to the tariffs for power from renewable energy sources as laid down in the Renewable Energy Sources Act (EEG). This has given rise to a sustained and strong demand that has led to the creation of a considerable number of biogas plant manufacturers and component suppliers,which has enabled Germany to become a market leader in thefield of the planning and construction of biogas plants.

Irrespective of country, the realisation of a biogas project hinges on four key issues,all of which are addressed by this Guide:

- A successful biogas project calls for comprehensive, multidisciplinary knowledge on the part of farmers, investors and future operators, allied to know-how about agriculture and energy technology, including all related statutory, environmental, administrative, organisational and logistical aspects.
- The market has offered up an almost bewildering array of technical options and customised solutions. This Guide gives a vendor-neutral and scientifically grounded overview of what technologies are currently available on the market and which hold out special promise for the future.
- When deciding on the appropriate substrates, it is necessary to apply and comply with elementary rules of biotechnology. Especially for the phases of concept formulation and plant operation, therefore,

this Guide makes available the knowledge needed to guarantee optimum operation of a biogas plant.
- Particularly in new markets, the permitting procedure for a biogas plant represents an important and often underestimated stepping stone on the path to project realisation. This Guide therefore provides an overview of the various steps required for realisation of a biogas project, with due consideration being given to the differences in permitting procedure between various countries.

The supply of renewable energy from biogas can be ideally combined with improved management of the material stream. Consequently, it often makes sense to invest in a biogas plant. To be able to arrive at a well-founded decision, however, prospective biogas plant operators must apply the correct methodology when comparing their own ideas with the technical and economic possibilities made available by biogas technology. For this reason, the Guide to Biogas provides the necessary information with which to fully exploit the potential offered by the biogas sector in terms of energy efficiency and economic profitability.

1.2 Approach

This Guide is designed to close any existing gaps in knowledge and to escort potential plant operators and other involved parties through the various planning phases of a biogas project through to project realisation.

The Guide is intended to **MOTIVATE** the reader to determine what opportunities are locally available and to examine whether and in what way he or she can contribute to recovering the energy contained in biogas. The present document is further intended to **INFORM**. To this end, it provides prospective plant operators and other parties interested in utilising the energy potential of biogas with all the required information from a single source. The Guide also presents the appropriate resources with which to **EVALUATE** a project idea. It delivers the tools required for a critical examination of a promising project idea in relation to its suitability for profitable implementation. A further object of the Guide is to furnish the reader with the knowledge and decision-making aids with which to **REALISE** a project idea to supply energy from biogas.

1.3 Contents

This Guide to Biogas gives the reader an overview of the complexities of the production and utilisation of biogas. It can be used as a reference source and checklist for all the considerations and actions necessary for the preparation, planning, construction and operation of a biogas plant. It takes account not only of the aspects of technology and engineering, but also of legal, economic and organisational factors. These subjects, which are addressed in depth in the individual chapters of the Guide, are first of all summarised here. With reference to the four approaches outlined above, this Guide is designed to offer support especially in relation to the following four subject areas:
- motivation to become involved
- imparting of basic information
- evaluation of a project idea
- realisation of a project.

Chapters 2 to 6 and 10 explain the basic principles of construction and operation of a biogas plant in addition to describing the use of substrates and residues. Chapters 7 to 9 deal with the statutory, administrativeand economic framework of biogas plant operation and farm business organisation. Chapter 11 is designed to facilitate the realisation of a biogas plant project, for which purpose it furnishes the reader with planning recommendations and checklists on plant construction, plant operation and contractual arrangements on the basis of the information contained in the preceding chapters. Chapter 12 is intended to provide the motivation to develop ideas and to launch initiatives. It also presents a series of arguments in favour of the production and utilisation of biogasas a support for public relations campaigns, which play a key role in the realisation of a project to recover energy from organic substrates in order to produce biogas.

1.4 Target groups

This Guide is addressed to all those who have an interest in the production and utilisation of biogas and/or who are in any way affected by a biogas project. It is thus aimed primarily at individuals or institutions concerned with the realisation of a biogas project. The target group of individuals seeking to realise a biogas project will include farmers or agricultural businesses and their partners. As substrate and energy producers, they have a potential interest in recovering and utilising the energy from biogas. Furthermore, the digestate from a biogas plant represents a higher-value fertiliser for use on a farm.

Further potential biogas producers include other-generators or recyclers of organic residues, such as waste disposal enterprises and local authorities. Private and institutional investors as well as energy utilities are likewise among the target group of potential realisers of biogas projects. There are, for example, venture capital companies that invest specifically in biogas projects.

The second target group is composed of individuals who are involved in some form or other in a biogas project, either in the capacity of government agency workers, bank employees, staff at power or gas grid operators, agricultural advisers or planners, or in the capacity of plant manufacturers or component suppliers.

However, this Guide is also addressed to anyone who is directly or indirectly affected by the realisation of a biogas project. It is designed to remedy any information deficits and to contribute to an improved understanding of mutual concerns.

The Guide is intended also as a source of motivation and assistance for decision-makers who, by virtue of their position, find themselves in the situation of initiating and/or launching a biogas project. This publication will be of help to potential subsidy-granting organisations and energy agencies in theirrole as multipliers.

1.5 Definition of scope

This version of the Guide has been adapted for an international readership on the basis of the German version developed by the Agency for Renewable Resources (FNR). Subject matter of a Germany-specific character has been omitted, while formulations and approaches with an international connection have been added. In consequence, not all the topics of relevance for developing countries and emerging economies can be examined here in detail. Emphasis has therefore been placed on presenting the technology required for efficient biogas production, which can subsequently be contrasted with the existing technologies in each individual country.

1.5.1 Technology

This Guide focuses exclusively on the use of biomass for the production and utilisation of biogas. The main emphasis is on plants in the agricultural sector as well as in the area of application concerned with the utilisation of residues from the processing of agricultural products. More especially, this Guide does not address the utilisation of, for example, municipal wastes and sewage sludges. Also, it focuses on those biogas technologies that have to a certain extent proved themselves in the marketplace and which have been commercially implemented on multiple occasions in Germany.

With regard to the utilisation of biogas, the emphasis is on combined heat and power generation (CHP). Small household systems for direct on-site gas utilisation employ a different, less capital-intensive technology (access to energy with minimum-possible capital investment) and are therefore not included here. While the upgrading of biogas to natural gas quality for feed-in to the natural gas grid is discussed in the present document, detailed analyses and evaluations are available in other publications, to which appropriate references are made.

There are other technologies that make use of biogas apart from engine-based CHP (such as microgasturbines or fuel cells, or using biogas for the local-supply of fuel), but these are discussed only in so far as scientifically validated information is available to demonstrate the economically worthwhile potential application of such technologies in the foreseeable future. This Guide, therefore, focuses on the production of biogas using commercially available processes and on the use of the biogas in an internal combustion engine to generate electric power by commercially available technology.

1.5.2 Substrates

The Guide deals with those substrates that are currently used on a significant scale in the German biogas sector, irrespective of their origin (agriculture, landscape maintenance, local authorities, industries using plant-based raw materials), as these are the substrates for which the largest body of empirical data is available. This publication places its emphasis on agricultural substrates and substrates from the food industry, since biogas markets, especially newly arising ones, will concentrate initially on available forms of biomass before additional substrates become adopted for widespread use. However, the basic principles described in this Guide can also be applied to other substrates, provided their digestion properties are known.

1.5.3 Currency of data

The ground work and data collection for this guide to the production to use of biogas were carried out in 2008 and 2009. Consequently, it describes the state of the art in biogas plants in Germany as at mid-2009. The discussion of the statutory framework, for example, makes reference to Germany's 2009 Act on Granting Priority to Renewable Energy Sources, which is subject to periodic amendment and is adapted in line with the market situation (most recently amended on 1 January 2012). In an international context, this Act can be seen as an example of how to successfully launch a market in biogas. Given different circumstances and framework conditions, it may be necessary to implement different measures in order to achieve positive results.

1.5.4 Scope of data

This Guide contains not only those facts and data that are necessary for an understanding of the relevant information and procedures, but also those that are required for making initial estimates and calculations. Any other data was omitted in the interests of greater clarity and transparency.

The Guide is the result of carefully conducted research and numerous discussions with experts. While the data is not claimed to be absolutely complete and accurate, the goal of a comprehensive and extensively exhaustive presentation of all relevant areas of biogas production and utilisation would appear to have been achieved.

Fundamentals of anaerobic digestion

2

2.1 Generation of biogas

As the name suggests, biogas is produced in a biological process. In the absence of oxygen (anaerobic means without oxygen), organic matter is broken down to form a gas mixture known as biogas. This process is widely found in nature, taking place in moors, for example, or at the bottom of lakes, in slurry pits and in the rumen of ruminants. The organic matter is converted almost entirely to biogas by a range of different microorganisms. Energy (heat) and new biomass are also generated.

The resulting gas mixture consists primarily of methane (50-75 vol. %) and carbon dioxide (25-50 vol. %). Biogas also contains small quantities of hydrogen, hydrogen sulphide, ammonia and other trace gases. The composition of the gas is essentially determined by the substrates, the fermentation (digestion) process and the various technical designs of the plants [2-1], [2-2], [2-3], [2-4]. The process by which biogas is formed can be divided into a number of steps (see Fig. 2.1). The individual stages of decomposition (degradation) must be coordinated and harmonised with each other in the best way possible to ensure that the process as a whole runs smoothly.

During the first stage, **hydrolysis**, the complex compounds of the starting material (such as carbohydrates, proteins and fats) are broken down into simpler organic compounds (e.g. amino acids, sugars and fatty acids). The hydrolytic bacteria involved in this stage release enzymes that decompose the material by biochemical means.

The intermediate products formed by this process are then further broken down during **acidogenesis** (the acidification phase) by fermentative (acid-forming) bacteria to form lower fatty acids (acetic, propionic and butyric acid) along with carbon dioxide and hydrogen. In addition, small quantities of lactic acid and alcohols are also formed. The nature of the products formed at this stage is influenced by the concentration of the intermediate hydrogen.

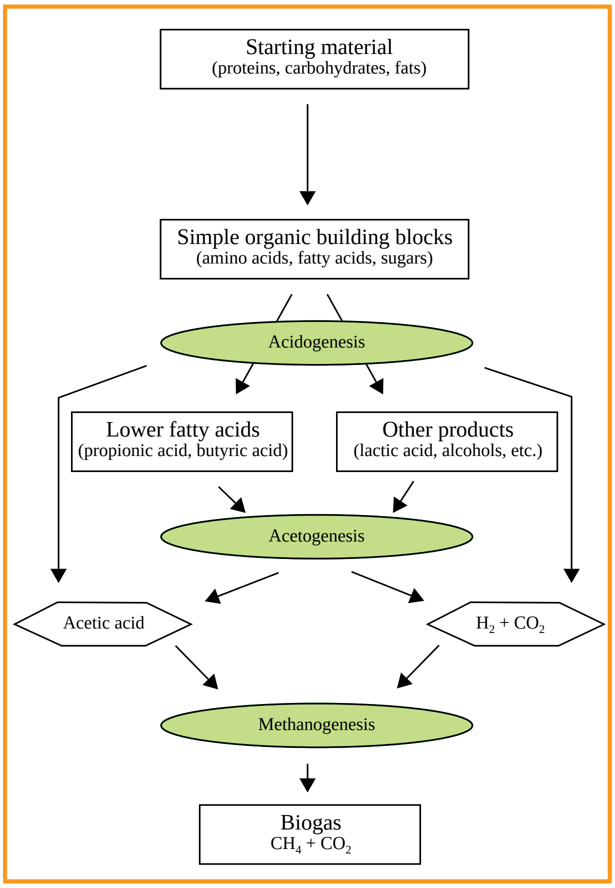

Figure 2.1: Schematic representation of anaerobic decomposition

In **acetogenesis**, the formation of acetic acid, these products are then converted by acetogenic bacteria into precursors of biogas (acetic acid, hydrogen and carbon dioxide). The hydrogen partial pressure is particularly important in this connection. An excessively high hydrogen content prevents the conversion of the intermediate products of acidogenesis, for energy-related reasons. As a consequence, organic acids, such as propionic acid, isobutyric acid, isovaleric acid and hexanoic acid, accumulate and inhibit the formation of methane. For this reason, the acetogenic bacteria (hydrogen-forming bacteria) must co-exist in a close biotic community (biocoenosis) with the hydrogen-consuming methanogenic archaea, which consume hydrogen together with carbon dioxide during the formation of methane (interspecies hydrogen transfer), thus ensuring an acceptable environment for the acetogenic bacteria [2-5].

During the subsequent **methanogenesis** phase, the final stage of biogas generation, above all acetic acid but also hydrogen and carbon dioxide are converted into methane by strictly anaerobic methanogenic archaea. The hydrogenotrophic methanogens produce methane from hydrogen and carbon dioxide, whereas the acetoclastic methane-forming bacteria produce methane by acetic acid cleavage. Under the conditions prevailing in agricultural biogas plants, at higher organic loading rates methane is formed primarily via the reaction pathway utilising hydrogen, while it is only at relatively low organic loading rates that methane is formed via the reaction pathway involving the cleavage of acetic acid [2-7], [2-8]. It is known from sewage sludge digestion that 70% of the methane originates from acetic acid cleavage and only 30% from hydrogen utilisation. In an agricultural biogas plant, however, this is true at best of high-capacity digesters with very short retention times [2-7], [2-9]. Recent research confirms that interspecies hydrogen transfer is plainly what determines the rate of methane formation [2-10].

Essentially, the four phases of anaerobic degradation take place simultaneously in a single-stage process. However, as the bacteria involved in the various phases of degradation have different requirements in terms of habitat (regarding pH value and temperature, for example), a compromise has to be found in the process technology. As the methanogenic microorganisms are the weakest link in biocoenosis on account of their low rate of growth and are the most sensitive to respond to disturbances, the environmental conditions have to be adapted to the requirements of the methane-forming bacteria. In practice, however, any attempt to physically separate hydrolysis and acidogenesis from methanogenesis by implementing two distinct process stages (two-phase process management) will succeed to only a limited extent because, despite the low pH value in the hydrolysis stage ($pH < 6.5$), some methane will still be formed. The resulting hydrolysis gas therefore also contains methane in addition to carbon dioxide and hydrogen, which is why the hydrolysis gas has to be utilised or treated in order to avoid negative environmental consequences and safety risks [2-11].

In multi-stage processes, different environments can become established in the individual digester stages depending on the design of the biogas plant and its operating regime, as well as on the nature and concentration of the fresh mass used as substrate. In turn, the ambient conditions affect the composition and activity of the microbial biocoenosis and thus have a direct influence on the resulting metabolic products.

2.2 Environmental conditions in the reactor

When describing the environmental conditions it is necessary to distinguish between wet digestion and solid-state digestion (also referred to as dry digestion), because the two processes differ significantly in terms of water content, nutrient content and mass transport. (The terms digestion and fermentation are also sometimes used interchangeably.) The descriptions in the following deal only with wet digestion, in light of its dominance in practice.

2.2.1 Oxygen

Methanogenic archaea are among the oldest living organisms on the planet, and came into being about three to four billion years ago, long before the atmosphere as we know it was formed. Even today, therefore, these microorganisms are still reliant on an environment devoid of oxygen. Most species are killed by even small quantities of oxygen. As a rule, however, it is impossible to completely prevent the introduction of oxygen into the digester. The reason why the activity of the methanogenic archaea is not immediately inhibited or why, in the worst case, they do not all die is that they coexist with oxygen-consuming bacteria from the preceding stages of degradation [2-1], [2-2]. Some of them are what are known as facultative anaerobic bacteria. These are capable of survival both under the influence of oxygen and also entirely without oxygen. Provided the oxygen load is not too high, they consume the oxygen before it damages the methanogenic archaea, which are totally reliant on an oxygen-free environment. As a rule, therefore, the atmospheric oxygen introduced into the gas space of the digester for the purposes of biological desulphurisation does not have a detrimental impact on the formation of methane [2-6].

From the biological standpoint a strict subdivision of the processes into wet and solid-state (dry) digestion is misleading, since the microorganisms involved in the digestion process always require a liquid medium in which to survive and grow.

Misunderstandings also repeatedly arise when defining the dry matter content of the fresh mass that is to be digested, since it is common practice to use several different substrates (feedstocks), each with a different dry matter content. In this connection it must be clear to the operator that it is not the dry matter content of the individual substrates that determines the classification of the process but the dry matter content of the substrate mixture fed into the digester.

Classification into wet or dry digestion therefore depends on the dry matter content of what is contained in the digester. It should again be pointed out that in both cases the microorganisms require sufficient water in their immediate environment.

Although there is no precise definition of the dividing line between wet and dry digestion, in practice it has become customary to talk of wet digestion when using energy crops with a dry matter content of up to approximately 12% in the digester, because the digester contents are generally still pumpable with this water content. If the dry matter content in the digester rises to 15-16% or more, the material is usually no longer pumpable and the process is referred to as dry digestion.

2.2.2 Temperature

The general principle is that the rate of chemical reactions increases with ambient temperature. This is only partially applicable to biological decomposition and conversion processes, however. In these cases it needs to be borne in mind that the microorganisms involved in the metabolic processes have different optimum temperatures [2-1]. If the temperature is above or below their optimum range, the relevant microorganisms may be inhibited or, in extreme cases, suffer irrevocable damage.

The microorganisms involved in decomposition can be divided into three groups on the basis of their temperature optima. A distinction is drawn between psychrophilic, mesophilic and thermophilic microorganisms [2-13]:

- Optimum conditions for psychrophilic microorganisms are at temperatures below 25 °C. At these temperatures although there is no need to heat the substrates or the digester, only low degradation performance and gas production can be achieved. As a rule, therefore, economic operation of biogas plants is not feasible.
- The majority of familiar methane-forming bacteria have their growth optimum in the mesophilic temperature range between 37 and 42 °C. Biogas plants operating in the mesophilic range are the most widespread in practice because relatively high gas yields and good process stability are obtained in this temperature range [2-6].
- If it is intended that harmful germs should be killed off by hygienisation of the substrate or if by-products or wastes with a high intrinsic temperature are used as substrates (process water, for example), thermophilic cultures are a suitable choice for the digestion process. These have their optimum in the temperature range between 50 and 60 °C. The high process temperature brings about a higher rate of decomposition and a lower viscosity. It must be taken into consideration, however, that more energy may be needed to heat the fermentation process. In this temperature range the fermentation process is also more sensitive to disturbances or irregularities in the supply of substrate or in the operating regime of the digester, because under thermophilic conditions there are fewer different species of methanogenic microorganisms present [2-6].

In practice it has been demonstrated that the boundaries between the temperature ranges are fluid, and it is above all rapid changes in temperature that cause harm to the microorganisms, whereas if the temperature changes slowly the methanogenic microorganisms are able to adjust to different temperature levels. It is therefore not so much the absolute temperature that is crucial for stable management of the process, but constancy at a certain temperature level.

The phenomenon of self-heating is frequently observed in practice, and should be mentioned in this connection. This effect occurs when substrates consisting largely of carbohydrates are used in combination with an absence of liquid input materials and well insulated containers. Self-heating is attributable to the production of heat by individual groups of microorganisms during the decomposition of carbohydrates. The consequence can be that in a system originally operating under mesophilic conditions the temperature rises to the region of 43 to 48 °C. Given intensive analytical backup and associated process regulation, the temperature change can be managed with small reductions in gas production for short periods [2-12]. However, without necessary interventions in the process (such as reduction of the input quantities), the microorganisms are unable to adapt to the change in temperature and, in the worst case, gas production can come to a complete halt.

2.2.3 pH value

The situation with regard to pH value is similar to that for temperature. The microorganisms involved in the various stages of decomposition require different pH values for optimum growth. The pH optimum of hydrolysing and acid-forming bacteria is in a range from pH 5.2 to 6.3, for example [2-6]. They are not totally reliant on this, however, and are still capable of converting substrates at a slightly higher pH value. The only consequence is that their activity is slightly reduced. In contrast, a pH value in the neutral range from 6.5 to 8 is absolutely essential for the bacteria that form acetic acid and for the methanogenic archaea [2-8]. Consequently, if the fermentation process takes place in one single digester, this pH range must be maintained.

Regardless of whether the process is single-stage or multi-stage, the pH value is established automatically within the system by the alkaline and acid metabolic products formed in the course of anaerobic decomposition [2-1]. The following chain reaction, however, shows just how sensitive this balance is.

If too much organic matter is fed into the process within too short a period of time, for example, or if methanogenesis is inhibited for some other reason, the acid metabolic products of acidogenesis will accumulate. Normally the pH value is established in the neutral range by the carbonate and ammonia buffer. If the system's buffer capacity is exhausted, i.e. if too many organic acids have built up, the pH value drops. This, in turn, increases the inhibitory effect of hydrogen sulphide and propionic acid, to the extent that the process in the digester comes to a halt within a very short space of time. On the other hand, the pH value is liable to rise if ammonia is released as a result of the breakdown of organic nitrogen compounds; the ammonia reacts with water to form ammonium. The inhibitory effect of ammonia consequently increases. With regard to process control, however, it must be borne in mind that because of its inertia although the pH value is of only limited use for controlling the plant, in view of its great importance it should always be measured.

2.2.4 Nutrient supply

The microorganisms involved in anaerobic degradation have species-specific needs in terms of macronutrients, micronutrients and vitamins. The concentration and availability of these components affect the rate of growth and the activity of the various populations. There are species-specific minimum and maximum concentrations, which are difficult to define because of the variety of different cultures and their – sometimes considerable – adaptability. In order to obtain as much methane as possible from the substrates, an optimum supply of nutrients to the microorganisms must be ensured. The amount of methane that can ultimately be obtained from the substrates will depend on the proportions of proteins, fats and carbohydrates they contain. These factors likewise influence the specific nutrient requirements [2-18].

A balanced ratio between macronutrients and micronutrients is needed to ensure stable management of the process. After carbon, nitrogen is the nutrient required most. It is needed for the formation of enzymes that perform metabolism. The C:N ratio of the substrates is therefore crucial. If this ratio is too high (a lot of C and not much N), inadequate metabolism may mean that the carbon present in the substrate is not completely converted, so the maximum possible methane yield will not be achieved. In the reverse case, a surplus of nitrogen can lead to the formation of excessive amounts of ammonia (NH_3), which even in low concentrations will inhibit the growth of the bacteria and, in the worst scenario, can lead to the complete collapse of the entire microorganism population [2-2]. For the process to run without disruption, the C:N ratio therefore needs to be in the range 10 – 30:1. Apart from carbon and nitrogen, phosphorus and sulphur are also essential nutrients. Sulphur is a constituent part of amino acids, and phosphorus compounds are necessary for forming the energy carriers ATP (adenosine triphosphate) and NADP (nicotinamide adenine dinucleotide phosphate). In order to supply the microorganisms with sufficient nutrients, the C:N:P:S ratio in the reactor should be 600:15:5:3 [2-14].

As well as macronutrients, an adequate supply of certain trace elements is vital for the survival of the microorganisms. The demand for micronutrients is generally satisfied in most agricultural biogas plants, particularly when the plant is fed with animal excrement. A deficiency in trace elements is very common in the mono-fermentation of energy crops, however. The elements that methanogenic archaea require are cobalt (Co), nickel (Ni), molybdenum (Mo) and selenium (Se), and sometimes also tungsten (W). Ni, Co and Mo are needed in cofactors for essential reactions in their metabolism [2-15], [2-16]. Magnesium (Mg), iron (Fe) and manganese (Mn) are also important micronutrients that are required for electron transport and the function of certain enzymes.

The concentration of trace elements in the reactor is therefore a crucial reference variable. A comparison of various sources in the literature on this topic reveals a strikingly large range of variation (sometimes by a factor of as much as 100) in the concentrations of trace elements considered essential.

Table 2.1: Favourable concentrations of trace elements according to various reference sources

Trace element	Concentration range [mg/l]			
	as in [2-18]	as in [2-19]	as in [2-16][a]	as in [2-17][b]
Co	0.003-0.06	0.003-10	0.06	0.12
Ni	0.005-0.5	0.005-15	0.006	0.015
Se	0.08	0.08-0.2	0.008	0.018
Mo	0.005-0.05	0.005-0.2	0.05	0.15
Mn	n.s.	0.005-50	0.005-50	n.s.
Fe	1-10	0.1-10	1-10	n.s.

a. Absolute minimum concentration in biogas plants
b. Recommended optimum concentration

The concentration ranges shown in Table 2.1 are only partly applicable to agricultural biogas plants because in some cases the studies described in these sources were carried out in the wastewater sector under different initial conditions and using different investigation methods. Furthermore, the spreads of these ranges are extremely wide, and very little detail is given of the prevailing process conditions (e.g. organic loading rate, retention time, etc.). The trace elements may form poorly soluble compounds with free phosphate, sulphide and carbonate in the reactor, in which case they are no longer available to the microorganisms. An analysis of the concentrations of trace elements in the feedstock can therefore provide no reliable information about the availability of trace elements, as it merely determines the total concentration. Consequently, larger quantities of trace elements have to be added to the process than would be needed solely to compensate for a deficient concentration. When determining requirements it is always necessary to take account of the trace element concentrations of all substrates. It is well known from analyses of the trace element concentrations of various animal feeds that they are subject to considerable fluctuation. This makes it extremely difficult to optimise the dosing of trace elements in situations where there is a deficiency.

Nevertheless, in order to prevent overdosing of trace elements, the concentration of micronutrients in the digester should be determined before trace elements are added. Overdosing can result in the concentration of heavy metals in the digestate (fermentation residue) exceeding the permissible limit for agricultural use, in which case the digestate cannot be used as organic fertiliser.

2.2.5 Inhibitors

There may be a variety of reasons why gas production is inhibited. These include technical causes affecting operation of the plant (cf. Section 5.4 Disturbance management). Substances known as inhibitors can also slow down the process. These are substances that, under certain circumstances, even in small quantities lower the rate of decomposition or, in toxic concentrations, bring the decomposition process to a standstill. A distinction must be drawn between inhibitors that enter the digester through the addition of substrate and those that are formed as intermediate products from the individual stages of decomposition.

When considering how a digester is fed it must be borne in mind that adding excessive substrate can also inhibit the digestion process, because any constituent of a substrate can have a harmful effect on the bacteria if its concentration is too high. This applies in particular to substances such as antibiotics, disinfectants, solvents, herbicides, salts and heavy metals, even small quantities of which are capable of inhibiting the decomposition process. The introduction of antibiotics is generally attributable to the addition of farm manure or animal fats, although the inhibitory effect of individual antibiotics varies greatly. However, even essential trace elements can also be toxic for the microorganisms if present in excessively high concentrations. As the microorganisms are able to adapt to such substances to a certain degree, it is difficult to determine the concentration as of which a substance becomes harmful [2-2]. Some inhibitors also interact with other substances. Heavy metals, for example, only have a harmful impact on the digestion process if they are present in solution. However, they are bonded by hydrogen sulphide, which is likewise formed in the digestion process, and precipitated out as poorly soluble sulphides. Since H_2S is almost always formed during methane fermentation, it is not generally to be expected that heavy metals will disrupt the process [2-2]. This is not true of copper compounds, however, which are toxic even at very low concentrations (40-50 mg/l) because of their antibacterial effect. On farms, these can enter the production cycle through hoof disinfection, for example.

A whole range of substances liable to inhibit the process are formed in the course of fermentation. Once again, though, it is worth drawing attention here to the great adaptability of bacteria: there cannot be assumed to be any generally applicable absolute limits. In particular, even low concentrations of non-ionic, free ammonia (NH_3) have a harmful impact on the bacteria; this free ammonia is in equilibrium with the ammonium concentration (NH_4^+) (ammonia reacts with water to form ammonium and an OH^- ion and vice versa). This means that with an increasingly alkaline pH value, in other words as the concentration of OH^- ions rises, the equilibrium is shifted and the ammonia concentration increases. A rise in pH value from 6.5 to 8.0, for example, leads to a 30-fold increase in the concentration of free ammonia. A rise in temperature in the digester also results in the equilibrium being shifted in the direction of ammonia with its inhibiting effect. For a digestion system that is not adapted to high nitrogen concentrations, the inhibition threshold is within a range from 80 to 250 mg/l NH_3 [2-2]. Depending on pH value and digestion temperature, this is equivalent to an ammonium concentration of 1.7-4 g/l. Experience shows that nitrogen inhibition of the biogas process must be expected at a total concentration of ammoniacal nitrogen of 3,000-3,500 mg/l [2-18].

Another product of the digestion process is hydrogen sulphide (H_2S), which in undissociated, dissolved form can inhibit the decomposition process as a cytotoxin at concentrations as low as 50 mg/l. As the pH value falls the proportion of free H_2S rises, increasing the risk of inhibition. One possible way of reducing the H_2S concentration is by precipitation as sulphides with the aid of iron ions. H_2S also reacts with other heavy metals, and is bonded and precipitated out accompanied by the formation of sulphide ions (S^{2-}) [2-2]. As previously mentioned, however, sulphur is also an important macronutrient. As an adequate concentration of sulphur is necessary for the formation of enzymes, excessive precipitation in the form of sulphides is liable, in turn, to inhibit methanogenesis.

The inhibitory effect of individual substances is therefore dependent on a number of different factors, and it is difficult to define fixed limit values. A list of

Table 2.2: Inhibitors in anaerobic decomposition processes and the concentrations at which they become damaging [2-14]

Inhibitor	Inhibitory concentration	Comments
Oxygen	> 0.1 mg/l	Inhibition of obligate anaerobic methanogenic archaea
Hydrogen sulphide	> 50 mg/l H_2S	Inhibitory effect rises with falling pH value
Volatile fatty acids	> 2,000 mg/l HAc (pH = 7.0)	Inhibitory effect rises with falling pH value. High adaptability of bacteria
Ammoniacal nitrogen	> 3,500 mg/l 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 Zn > 150 mg/l Cr > 100 mg/l	Only dissolved metals have an inhibitory effect. Detoxification by sulphide precipitation
Disinfectants, antibiotics	n.s.	Product-specific inhibitory effect

2.3 Operating parameters

2.3.1 Organic loading rate and retention time of the digester

Whenever a biogas plant is being designed and built, most attention is normally paid to economic considerations. Consequently, when the size of digester is being chosen the focus is not necessarily on maximum gas yield or on complete decomposition of the organic matter contained in the substrate. If it was intended to achieve complete decomposition of the organic constituents, sometimes very long retention times would be needed for the substrate in the digester, together with correspondingly large tank volumes, because some substances take a very long time to break down – if at all. The aim must therefore be to obtain optimum degradation performance at acceptable economic cost.

In this regard the organic loading rate (OLR) is a crucial operating parameter. It indicates how many kilograms of volatile solids (VS, or organic dry matter – ODM) can be fed into the digester per m^3 of working volume per unit of time [2-1]. The organic loading rate is expressed as kg VS/($m^3 \cdot d$).

$$B_R = \frac{\dot{m} \cdot c}{V_R \cdot 100} \quad [\text{kg VS m}^{-3}\ \text{d}^{-1}]$$

Equation 2.1: Organic loading rate (OLR)
($\dot{m}$ = amount of substrate added per unit of time [kg/d]; c = concentration of organic matter (volatile solids) [% VS]; V_R = reactor volume [m³])

The organic loading rate can be specified for each stage (gas-tight, insulated and heated vessel), for the system as a whole (total working volumes of all stages) and with or without the inclusion of material recirculation. Changing the reference variables can lead to sometimes widely differing results for the organic loading rate of a plant. To obtain the most meaningful comparison of the organic loading rates of various biogas plants it is advisable to determine this parameter for the entire system without considering material recirculation, in other words exclusively for the fresh substrate.

Another relevant parameter for deciding on the size of vessel is the hydraulic retention time (HRT). This is the length of time for which a substrate is calculated to remain on average in the digester until it is discharged [2-1]. Calculation involves determining the ratio of the reactor volume (V_R) to the volume of substrate added daily ($\dot{V}$) [2-2]. The hydraulic retention time is expressed in days.

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

Equation 2.2: Hydraulic retention time
(V_R = reactor volume [m³]; $\dot{V}$ = volume of substrate added daily [m³/d])

The actual retention time will differ from this, because individual components are discharged from the digester at different rates depending on the degree of mixing, for example as a result of short-circuit flows. There is a close correlation between the organic loading rate and the hydraulic retention time (Fig. 2.2).
If the composition of the substrate is assumed to remain the same, as the organic loading rate rises more input is added to the digester, and the retention time is consequently shortened. In order to be able to maintain the digestion process, the hydraulic retention time must be chosen such that constant replacement of the reactor contents does not flush out more microorganisms than can be replenished by new growth during that time (the doubling rate of some methanogenic archaea, for example, is 10 days or more) [2-1]. It should also be borne in mind that with a short retention time the microorganisms will have little time to degrade the substrate and consequently the gas yield will be inadequate. It is therefore equally important to adapt the retention time to the specific decomposition rate of the substrates. If the quantity added per day is known, the necessary reactor volume can be calculated in conjunction with the degradability of the substrate and the targeted retention time.

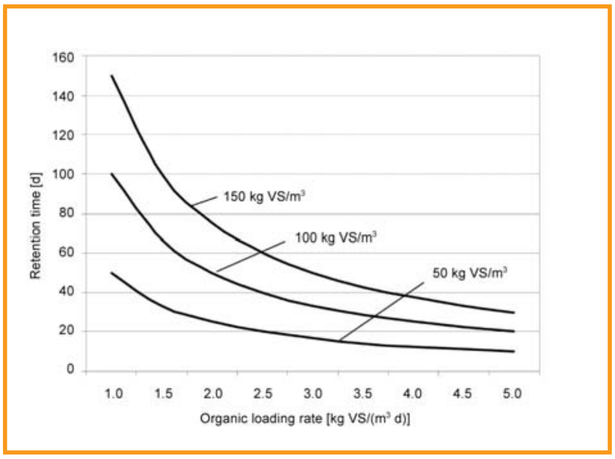

Figure 2.2: Correlation between organic loading rate and hydraulic retention time for various substrate concentrations

The primary purpose of the above-outlined operating parameters of a biogas plant is to describe the load situation, for example to compare different biogas plants. It is only during the start-up process that the parameters can help with plant control in terms of achieving a slow, steady rise. Normally, most attention is paid to the organic loading rate. In the case of plants with large volumes of liquid on the input side and a low content of degradable organic material (slurry plants), the retention time is more important.

2.3.2 Productivity, yield and degree of degradation

Productivity ($P_{(CH_4)}$), yield ($A_{(CH_4)}$) and degree of degradation (η_{VS}) are appropriate parameters for describing the performance of a biogas plant. If gas production is given in relation to digester volume, this is referred to as the productivity of the plant. This is defined as the quotient of daily gas production and reactor volume, and is consequently an indication of the plant's efficiency [2-20]. Productivity can be related to both biogas production ($P_{(biogas)}$) and methane production ($P_{(CH_4)}$) and is given in Nm³/(m³ · d).

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

Equation 2.3: Methane productivity ($\dot{V}_{(CH_4)}$ = methane production [Nm³/d]; V_R = reactor volume [m³])

Gas production expressed in relation to the input materials is the yield [2-8]. The yield can likewise be related to biogas production ($A_{(biogas)}$) or methane production ($A_{(CH_4)}$). This is defined as the quotient of the volume of gas produced and the amount of organic matter added, and is given in Nm^3/t VS.

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

Equation 2.4: Methane yield ($\dot{V}_{(CH_4)}$= methane production [Nm³/d]; $\dot{m}_{VS}$ = added volatile solids [t/d])

The yields denote the efficiency of biogas production or methane production from the loaded substrates. They are of little informative value as individual parameters, however, because they do not include the effective loading of the digester. For this reason, the yields should always be looked at in connection with the organic loading rate.

The degree of degradation (η_{VS}) provides information about the efficiency with which the substrates are converted. The degree of degradation can be determined on the basis of volatile solids (VS) or chemical oxygen demand (COD). Given the analytical methods most commonly used in practice, it is advisable to determine the degree of degradation of the volatile solids [2-20].

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

Equation 2.5: Degree of degradation (η_{VS}) of biomass (VS_{Sub} = volatile solids of added fresh mass [kg/t FM]; m_{zu} = mass of added fresh mass [t]; VS_{Abl} = volatile solid content of digester discharge [kg/t FM]; m_{Abl} = mass of digestate [t])

2.3.3 Mixing

In order to obtain high levels of biogas production there needs to be intensive contact between bacteria and the substrate, which is generally achieved by thorough mixing in the digestion tank [2-1]. Unless thorough mixing takes place in the digester, after a certain time demixing of the contents can be observed along with the formation of layers. This is attributable to the differences in density of the various constituents of the substrates and also to upthrust from the formation of gas. In this event the bulk of the bacterial mass collects in the lower layer, as a result of its higher density, whereas the substrate to be decomposed often collects in the upper layer. In such cases the contact area is limited to the boundary area between these two layers, and little degradation takes place. Furthermore, some solids float to the top to form a layer of scum that makes it more difficult for gas to escape [2-21].

It is important, therefore, to promote contact between microorganisms and substrate by mixing the contents of the digestion tank. Excessive mixing should be avoided, however. In particular the bacteria that form acetic acid (active in acetogenesis) and the archaea in methanogenesis form a close biotic community that is enormously important if the process of biogas formation is to proceed undisturbed. If this biotic community is destroyed by excessive shear forces as a result of intensive stirring, anaerobic decomposition can be negatively affected.

A compromise therefore needs to be found in which both conditions are adequately satisfied. In practice this is usually achieved with slowly rotating agitators that exert only low shear forces, but also by the contents of the reactor being mixed thoroughly at certain intervals (i.e. just for a short, predefined length of time). Further technical questions relating to mixing are discussed in Section 3.2.2.3.

2.3.4 Gas generation potential and methanogenic activity

2.3.4.1 Possible gas yield

The amount of biogas produced in a biogas plant essentially depends on the composition of the substrates. In order to determine this, if possible a digestion test should be carried out with the relevant substrate mixture [2-22]. Failing that, the gas yield can be estimated from the sum of the gas yields of the substrates making up the input, assuming that the gas yield values for the individual substrates are available from reference tables [2-23].

For less common substrates for which no data is available from digestion tests, the gas yield can be estimated with the aid of the digestion coefficient, because there are parallels between the decomposition processes in a biogas plant and the digestion processes in ruminants [2-3]. The figures required for this can be taken from the German Agricultural Society's (DLG) feed composition tables in the case of renewable raw materials (energy crops). These show the concentrations of crude ash (CA), crude fibre (CF), crude lipids (CL), crude protein (CP) and nitrogen-free extract (NFE) relative to dry matter (DM) from Weende feed analysis, and their digestibility coefficients (DC). The CF and NFE concentrations taken together form the carbohydrate concentration.

The various substance groups can be assigned specific gas yields and methane concentrations, which derive from the different relative carbon concentrations in each case (Table 2.3) [2-6], [2-25].

This data can be used to calculate the volatile solids and the respective mass of the digestible substance groups per kg of dry matter [2-24]:

VS concentration:
(1000 - crude ash[1])/10 [% DM]
Digestible protein:
(crude protein · DC_{CP})/1000 [kg/kg DM]
Digestible fat:
(crude fat · DC_{CL})/1000 [kg/kg DM]
Digestible carbohydrates:
((crude fibre · DC_{RF}) + (NFE · DC_{NFE}))/1000 [kg/kg DM]

[1] in g/kg

The further calculation is illustrated using the example of **grass silage** (extensive pasture, first growth, mid-bloom) (Table 2.4).

Calculation:
VS concentration:
(1000 - 102)/10 = **89.8% (DM)**
Digestible protein:
(112 · 62%)/1000 = **0.0694 kg/kg DM**
Digestible fat:
(37 · 69%)/1000 = **0.0255 kg/kg DM**
Digestible carbohydrates:
((296 · 75%) + (453 · 73%))/1000 = **0.5527 kg/kg DM**

The masses of the individual substance groups per kg of volatile solids can therefore be calculated in this way. These results are multiplied by the values from Table 2.3 to obtain the biogas and methane yields shown in Table 2.5.

According to this, 162.5 litres of biogas with a methane content of approximately 53% is obtained per kg of fresh mass. In this context it must be expressly stated that in most cases the methane yields achieved in practice will be significantly higher than the calculated yields. According to current knowledge there is no sufficiently statistically robust method of calculating the specific gas yield with any precision. The method described here merely allows a comparison to be made between different substrates.

However, a number of other factors also affect the attainable biogas yield, such as the retention time of the substrates in the digester, the total solids content, the fatty acid content and any inhibitors present. An increase in retention time, for example, improves the degree of degradation and consequently also raises gas production. As the retention time increases, more and more methane is released, which increases the calorific value of the gas mixture.

Raising the temperature also accelerates the rate of degradation. This is only feasible to a limited extent, however, because once the maximum temperature is exceeded the bacteria suffer harm and the converse effect is achieved (see Section 2.2.2). However, not only is gas production increased, but also more carbon dioxide is released from the liquid phase, which in turn

Table 2.3: Specific biogas yield and methane concentration of the respective substance groups [2-25]

	Biogas yield [l/kg VS]	Methane concentration [vol. %]
Digestible protein (CP)	700	71
Digestible fat (CL)	1,250	68
Digestible carbohydrates (CF + NFE)	790	50

Table 2.4: Parameters for grass silage

DM [%]	Crude ash (CA) [g/kg DM]	Crude protein (CP) [g/kg DM]	DC_{CP} [%]	Crude lipids (CL) [g/kg DM]	DC_{CL} [%]	Crude fibre (CF) [g/kg DM]	DC_{CF} [%]	NFE [g/kg DM]	DC_{NFE} [%]
35	102	112	62	37	69	296	75	453	73

Table 2.5: Biogas and methane yields from grass silage

	Biogas yield [l/kg VS]	Methane yield [l/kg VS]
Digestible protein (CP)	48.6	34.5
Digestible fat (CL)	31.9	21.7
Digestible carbohydrates (CF + NFE)	436.6	218.3
Total (per kg VS)	**517.1**	**274.5**

As already explained at the beginning of this chapter, while there are certainly parallels between the processes taking place in the rumen of ruminants and the decomposition processes in a biogas plant, the two processes are not entirely comparable because different synergy effects can arise in each of these 'systems', influencing the production of biogas. The calculation method presented here is therefore only suitable for estimating the actual gas or methane yield and consequently should **not** be used for operational or economic calculations. This method does however make it possible to estimate trends in biogas yield and to draw comparisons between different substrates.

results in the gas mixture having a lower calorific value.

The content of dry matter in the digester (total solids: TS) can affect gas yield in two ways. Firstly, mass transport is impeded if the TS content is high, to the extent that microorganisms are only able to decompose the substrate in their immediate vicinity. At very high total solids contents of ≥40% digestion can even come to a complete standstill, as there is no longer sufficient water present for microorganism growth. Secondly, a high content of total solids can cause problems with inhibitors, as these are present in concentrated form because of the low water content. Mechanical or thermal pretreatment of the substrates can increase yield because it improves the availability of substrate for the bacteria [2-4].

2.3.4.2 Gas quality

Biogas is a gas mixture that is primarily made up of methane (CH_4) and carbon dioxide (CO_2), along with water vapour and various trace gases.

The most important of these is the methane content, since this is the combustible component of biogas and thus directly influences its calorific value. There is only limited opportunity for influencing the composition of biogas by means of selective process control. First and foremost the composition of the biogas is dependent on the composition of the input material. In addition, the methane content is affected by process parameters such as the digestion temperature, reactor loading and hydraulic retention time, as well as by any disruptions to the process and the method of biological desulphurisation used.

The achievable methane yield is essentially determined by the composition of the substrate, in other words by the proportions of fats, proteins and carbohydrates (see Section 2.3.4.1). The specific methane yields of these substance groups diminish in the order listed above. Relative to their mass, a higher methane yield can be achieved with fats than with carbohydrates.

With regard to the quality of the gas mixture, the concentration of the trace gas hydrogen sulphide (H_2S) has an important part to play. It should not be too high, because even low concentrations of hydrogen sulphide can have an inhibitory effect on the degradation process. At the same time high concentrations of H_2S in biogas cause corrosion damage when used in a combined heat and power unit or heating boiler [2-1]. An overview of the average composition of biogas is given in Table 2.6.

Table 2.6: Average composition of biogas (after [2-1])

Constituent	Concentration
Methane (CH_4)	50-75 vol. %
Carbon dioxide (CO_2)	25-45 vol. %
Water (H_2O)	2–7 vol. % (20-40 °C)
Hydrogen sulphide (H_2S)	20-20,000 ppm
Nitrogen (N_2)	< 2 vol. %
Oxygen (O_2)	< 2 vol. %
Hydrogen (H_2)	< 1 vol. %

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3 Plant technology for biogas recovery

Plant technology for biogas recovery covers a very wide spectrum, as discussed in this chapter. There are virtually no limits in terms of component and equipment combinations. Consequently, technical examples are used here by way of illustration of individual items of equipment. It must be noted, however, that expert analysis of plant and system suitability and capacity adaptation on a case-to-case basis are invariably required.

Turnkey supply by a single provider, known as the lead contractor, is common practice in the construction of biogas plants, and this has both advantages and disadvantages for the project owner. A turnkey provider generally uses end-to-end technology and provides a warranty for the individual items of equipment and the plant as a whole, and this can be considered advantageous. The functionality of the process for generating biogas is also part of the warranty. When a lead contractor undertakes supply, the finished plant is usually not handed over to the project owner until performance trials have been completed, in other words not until the plant has achieved rated load. This is an important consideration, because firstly the risk associated with plant run-up resides with the manufacturer, and secondly there is no financial risk to be borne by the future operator if handover is delayed. One drawback is the relatively minor influence that the project owner can exert on technological details, because very many turnkey providers offer standardised modules and this makes for less flexibility in terms of design specifics. Nevertheless, the modular approach has timeline and monetary advantages to offer in terms of approval, construction and operation.

Project owners can also go down another path, and purchase only planning services from the plant supplier (engineering contact). The project owner then contracts out individual construction phases to specialist companies. This approach enables the project owner to maximise influence on the project, but it is viable only if the project owner per se is in possession of the necessary expertise. Disadvantages include the facts that the risk for start-up and performance trials has to be borne by the project owner and that if claims against the specialist contractors arise, they have to be dealt with individually.

3.1 Features of and distinctions between various procedural variants

There are several variant processes for generating biogas. Typical variants are shown in Table 3.1.

Table 3.1: Classification of the processes for generating biogas according to different criteria

Criterion	Distinguishing features
Dry matter content of the substrate	- wet digestion - dry digestion
Type of feed	- intermittent - quasi-continuous - continuous
Number of process phases	- single-phase - two-phase
Process temperature	- psychrophilic - mesophilic - thermophilic

3.1.1 Dry matter content of the substrate for digestion

The consistency of the substrate depends on its dry matter content. This is the reason for a basic subdivision of biogas technology into wet-digestion and dry-digestion processes. Wet digestion uses substrates of pumpable consistency. Dry digestion uses stackable substrates.

There is no clear dividing line between the terms wet and dry digestion. A design guide issued by the Federal German Ministry for the Environment on the basis of the Renewable Energy Sources Act (EEG) of 2004 links 'dry digestion' to certain provisions. These provisions include a dry mass content of at least 30% by mass in the feedstock and an organic loading rate of at least 3.5 kg $_{VS}/(m^3 \cdot d)$ in the digester.

The dry matter content in digester liquid in the wet digestion process can be up to 12% by mass. A rule of thumb sets a limit of 15% by mass for the pumpability of the medium, but the figure is qualitative and not viable for all feedstock materials. Some substrates with finely dispersed particle distribution and high proportions of dissolved substances remain pumpable even when DM content is as high as 20% by mass; dispersed foodstuff residues discharged from tankers are a case in point. Other substrates such as fruit peel and vegetable skins, by contrast, are stackable when DM content is as low as 10 to 12% by mass.

Wet digestion in ordinary cylindrical tanks is the norm for agricultural-scale biogas recovery plants. Over the last five years, however, following the 2004 first amendment to EEG, dry-digestion plants have progressed to marketable maturity and are used in particular for digesting energy crops, the renewables generally termed 'NawaRo' in German (nachwachsende Rohstoffe, or renewable resources). See 3.2.2.1 for details of digester designs.

3.1.2 Type of feed

The biogas recovery plant's loading or feeding regime determines to a large extent the availability of fresh substrate for the microorganisms and has a corresponding effect on the generation of biogas. Broad distinctions are drawn between continuous, quasi-continuous and intermittent feeding.

3.1.2.1 Continuous and quasi-continuous feeding

A further distinction can be drawn here between the through-flow and combination through-flow/buffer-tank methods. The buffer-tank-only feeding method of which some mention can still be found in the literature is not discussed here, because economical and process-engineering considerations now virtually preclude its use. In contrast to continuous feeding, quasi-continuous feeding entails adding to the digester an unfermented batch of substrate at least once per working day. There are further advantages to be gained by adding the substrate in several small batches over the course of the day.

Through-flow method

In the past, most biogas recovery systems were built to operate on the through-flow principle. Several times a day, substrate is pumped from a pre-digester tank or pre-digester pit into the reactor. The same quantity as is added to the digester in the form of fresh substrate is expelled or extracted to the digestate storage tank (see Figure 2.1).

This feeding method therefore maintains a constant level of fill in the digester, which is emptied only for repairs. Steady gas production and good utilisation of reactor space are characteristic of this process. However, there is a risk of short-circuited flow through the digester, because there is always the possibility of freshly added substrate being more or less immediately removed [3-2]. The open digestate storage tank, moreover, is a source of methane gas emissions. The 2009 second amendment to the Renewable Energy Sources Act calls for sealed, gastight digestate storage, so the purely through-flow process will be of lessening significance in future.

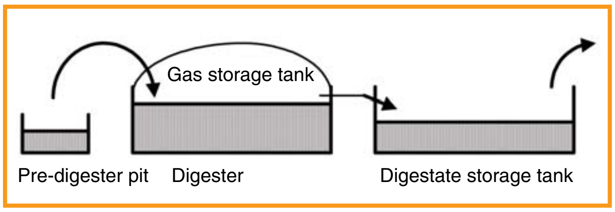

Figure 3.1: Schematic of the through-flow process

Combination through-flow/buffer-tank process

Biogas recovery plants operating on the combination through-flow/storage-tank principle also employ covered digestate storage facilities. This enables the post-digestion biogas arisings to be captured and used. The digestate storage tank functions as a 'buffer tank'. The unit upstream of this buffer tank part of the plant is a through-flow digester. If, say, the need arises for a large quantity of pre-digested substrate as fertiliser, substrate can be removed from the through-flow digester. Figure 3.2 is a diagrammatic overview of the process. The process permits steady gas production. The dwell time cannot be accurately determined, on account of the possibility of flow short-circuits in the through-flow digester [3-2]. This process represents the state of the art. The investment outlay for covering the digestate storage tank can be successively refinanced from income for the extra gas yield.

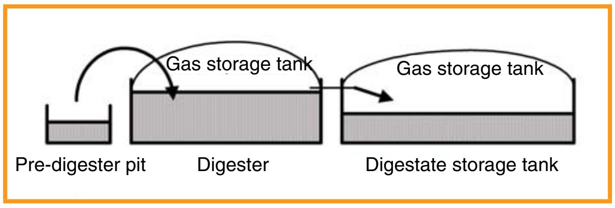

Figure 3.2: Schematic of the combination through-flow/buffer-tank process

3.1.2.2 Intermittent feeding

Batched, intermittent feeding entails completely filling the digester with fresh substrate and then establishing an airtight seal. The feedstock remains inside the tank until the selected dwell time elapses, without any substrate being added or removed during this time. When the dwell time expires the digester is emptied and refilled with a fresh batch of feedstock, with the possibility of a small proportion of the digestate being allowed to remain as seed material to inoculate the fresh substrate. The process of filling the batch digester is speeded up by providing a supply tank, with a discharge storage vessel for the same purpose at the output side. A gas production rate that changes over time is characteristic of intermittent, batch feeding. Gas production commences slowly after the reactor has been filled, peaks within a few days (depending on substrate) and then steadily tails off. Since a single digester cannot ensure the constancy of gas production or gas quality, staggered filling of several digesters (battery batch-feed method) has to be adopted to smooth out net production. Minimum dwell time is accurately maintained [3-2]. Batch feeding of single digesters is impractical; the principle of battery batch feeding is used for dry digestion in what are sometimes known as 'digester garages' or 'modular box digesters'.

3.1.3 Number of process phases and process stages

A process phase is understood as the biological milieu – hydrolysis phase or methanisation phase – with its specific process conditions such as pH value and temperature. When hydrolysis and methanisation take place in a single tank the term used is single-phase process management. A two-phase process is one in which hydrolysis and methanisation take place in separate tanks. Stage is the term used for the process tank, irrespective of the biological phase.

Consequently, the plant layout with pre-digester pit, digester and digestate storage tank frequently encountered in agriculture is single-phase, but three-stage. The open pre-digester pit as such is not a separate phase in its own right. The sealed holding or receiving vessel, on the other hand, is considered a separate phase (hydrolysis phase). Main and secondary digesters both belong to the methanisation phase.

In the main, agricultural biogas recovery plants are of single-phase or two-phase design, and single-phase plants are the more common [3-1].

3.2 Process engineering

Broadly speaking, irrespective of the operating principle an agricultural biogas plant can be subdivided into four different process steps:

1. substrate management (delivery, storage, preparation, transport and infeed)
2. biogas recovery
3. digestate storage, treatment and field spreading
4. biogas storage, treatment and use.

The individual steps are shown in more detail in Figure 3.3.

The four process steps are not independent of each other. The link between steps two and four is particularly close, because step four generally provides the process heat needed for step two.

The treatment and use of the biogas belonging to step 4 are discussed separately in Chapter 6; Chapter 10 deals with the processing and treatment of digestate. The information below relates to the technology and techniques employed in steps 1, 2 and 3.

The choice of process equipment depends primarily on the nature of the available substrates. All plant and container sizing has to be based on substrate quantities. Substrate quality (DM content, structure, source, etc.) is the determining factor in terms of process-engineering design. Depending on substrate composition, it can be necessary to remove interfering substances or wet down with make-up liquid to obtain a pumpable mash. If substances that require hygienisation are used, planning has to allow for a hygienisation stage. After pretreatment, the substrate is moved to the digester, where it ferments.

Wet-digestion plants are generally of one- or two-stage design, operating on the through-flow principle. A two-stage layout consists of digester and secondary digester. The substrate is moved from the first, or primary, digester to the secondary digester, where more resistant substances also have the opportunity to biode-

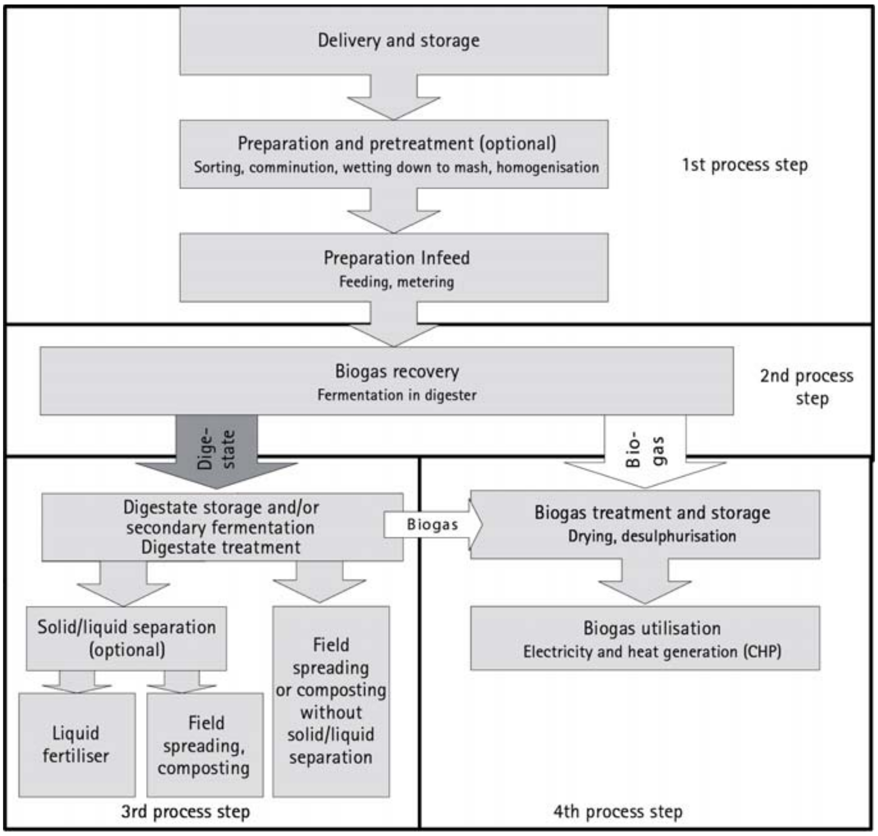

Figure 3.3: General process of biogas recovery; as described in [3-3]

grade. The digestate is stored in sealed digestate storage tanks with biogas extraction or open digestate tanks and is then generally disposed by being spread as liquid fertiliser on agricultural land.

The biogas produced by biodegradation of the feedstock is stored and purified. It is generally fired in a combined heat and power (CHP) unit for co-generating electricity and heat. Figure 3.4 shows the most important plant components, subassemblies and units of a single-stage agricultural biogas recovery plant for co-substrates with hygienisation.

The process steps as illustrated here are as follows: The liquid-manure pit (or pre-digester pit) (2), the header (3) and hygienisation tank (4) all belong to the first process step (storage, preparation, transport and infeed) The second process step (biogas recovery) takes place in the biogas reactor (5), more commonly called the digester. The liquid-manure storage tank (8) or the digestate storage tank and the field spreading of the digested substrate (9) constitute the third process step. The fourth process step (biogas storage, purification and utilisation) takes place in the gas tank (6) and the combined heat and power unit (7). These individual steps are discussed in more detail below.

3.2.1 Substrate management

3.2.1.1 Delivery

The role played by delivery is of importance only in plants digesting co-substrates from off-site sources. Visual incoming inspection of the substrate to ensure compliance with quality standards is the minimum requirement for custody-transfer accounting and for documentation purposes. Large-scale facilities designed to digest energy crops are making increasing use of rapid testing methods to check dry matter and in some cases the fodder fractions as well, to ensure compliance with the conditions set out in the contract of supply on the one hand and performance-based payment on the other.

In principle, the as-delivered weight has to be measured and all goods-incoming data have to be logged. Substrates classed as waste merit special consideration. Depending on precisely how the waste is classified, it might be necessary to keep special records or comply with specific documentation requirements imposed by the authorities. This is why backup samples of critical substances are taken. See

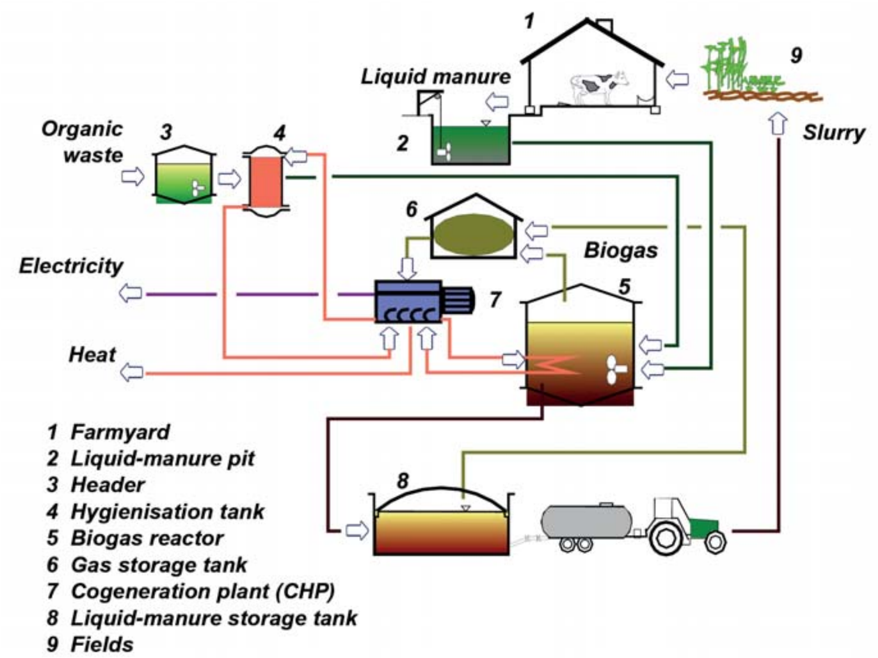

Figure 3.4: Schematic of an agricultural biogas recovery plant for co-substrates [ATB]

Chapter 7 for more information on the general legal and administrative framework.

3.2.1.2 Storage

Substrate buffer storage facilities are intended primarily for buffering the quantities of substrate needed as digester feedstock for periods ranging from a few hours up to two days. The design of the storage facility depends on the types of substrate used. Footprint varies with the quantities that the facility will have to handle and the time periods for which substrate will have to be buffered. If co-substrates from off-site sources are used, contractual conditions such as agreed acceptance quantities and frequency of supply factor into the considerations. Using hygienically problematic co-substrates from industrial sources, for example, necessitates strictly segregating the receiving station from farming operations. Intermingling of hygienically problematic and hygienically acceptable substrates at any point prior to the former's discharge from hygienisation must be impossible.

Table 3.2: Pre-digestion storage of substrates

Sizing	• Depends on: substrate arisings, digester capacity, length of time to be bridged between successive deliveries, land-use specifics and yield of co-substrates, supply contracts for substrates from off-site sources, possible disruptions in operation
Special considerations	• Avoid the possibility of storage plant freezing, for example by siting storage tanks indoors, heating storage containers or locating the plant for pits below grade level • Avoid biodegradation processes that reduce gas yield • Do not permit intermingling of hygienically problematic and hygienically acceptable substrates • Implement suitable structural measures to minimise odours • Avoid material emissions to soil and to the surface and underground water system
Designs	• Containers for storing solid substrates in widespread use in agriculture, such as mobile silos, upright silos, plastic-tunnel silos and round-bale silos and open or roofed storage areas (e.g. solid-manure deposits) and pits/hoppers • Containers for storing liquid substrates in widespread use in agriculture, such as tanks and pre-digester pits
Costs	• Storage facilities are generally in place; when new builds are needed the price has to be calculated on a case-to-case basis factoring in the multiplicity of influencing variables indicated above

There are other reasons besides legal considerations for using sealed storage facilities to minimise odours. Enclosure in sheds is one possibility, and structures of this nature can include spaces for receiving and preparing the substrates, along with storage as such. The spent air can be extracted and ducted through suitable cleaners (e.g. washers and/or biofilters). The sheds for waste-product digesters frequently have negative-pressure systems which, along with waste-air extraction, largely prevent odour emissions. Sheds have other advantages as well as the potential for odour emissions. They offer the equipment a measure of protection, and work and checks can be carried out irrespective of weather conditions. Enclosure can also be a means of achieving compliance with noise-abatement regulations. Table 3.2 presents an overview of various aspects of substrate storage.

3.2.1.3 Preparation

The nature and extent of substrate preparation influence the general usability of substrates with regard to the proportion of entrained interfering substances, so they factor directly into the availability of plant technology. Moreover, a suitable preparation process can have a positive effect on the digestion-process transient, which in turn affects utilisation of the substrates' energy potential.

Figure 3.5: In-pipe separator for dense materials [DBFZ]

Sorting and removal of interfering substances

The necessity for sorting and removal of interfering substances depends on the origin and the composition of the substrate. Stones are the most common; they generally settle out in the pre-digester pit, where from time to time they have to be removed from the bottom. Separators for dense materials are also used, generally sited directly in the substrate pipe in front of the feed conveyor (see Figure 3.5). Other matter has to be removed manually at the point of substrate delivery or during filling of the feed hoppers. There is considerable likelihood that biowaste materials may contain interfering substances. Whenever material of this nature is used as co-substrate, every effort should be made to ensure that it is not freighted with interfering substances. Most farming operations would not have the resources to install complex sorting facilities with mechanical lines or sorting boxes comparable with those in dedicated biowaste processing plants. Modular-box or garage digesters, by contrast, are virtually unaffected by interfering substances, because wheeled loaders and grabs are the primary means of substrate transport and there is no contact with pumps, valves or screw conveyors or other components of similar nature that would be easily damaged by interfering substances.

Comminution

Comminution increases the aggregate substrate surface area available for biodegradation and consequently for methanisation. Broadly speaking, although breaking down the size of the particles effectively accelerates the rate of biodegradation, it does not necessarily increase gas yield. The interplay of dwell time and degree of comminution is one of the factors influencing methane production. Hence the importance of adopting the appropriate technology.

The equipment for comminuting solid substrates can be sited externally upstream from the point of infeed, in the pre-digester pit, pipe or digester. The range of equipment includes chippers, mills, crushers and shafts and screw conveyors with rippers and cutters (see Figure 3.7). Shafts with paddles and bladed screw conveyors are very common in combined receiving and metering units (see Figure 3.6). Given the extent of their application, the properties of these comminution devices are summarised separately for handling direct solids metering by combined receiving and metering units (in Table 3.3) and processing by mills and chippers (in Table 3.4).

By contrast with comminution of solids before transfer to pre-digester pit, pipeline or digester, liquids with solid or fibrous content can be comminuted directly in the pre-digester pit, in other mixing tanks or in the pipeline. This can be necessary in the case of substrates and substrate mixtures the consistency of which could threaten the operability of the feeder (generally a pump). Separate comminution agitators sited in the pit

Figure 3.6: Receiving vessel with loosener [Konrad Pumpe GmbH]

upstream of the digester constitute one means of comminution. In-pipe, directly linked comminution and pumping is common, however, and the same applies to combination comminution/pumping units. These units are generally powered by electric motors, and some are designed to be driven off a tractor PTO. Figures 3.8 and 3.9 show comminutors of various designs and the properties of these machines are summarised in Tables 3.5 to 3.7.

Table 3.3: Characteristic values and process parameters of comminutors in combined receiving and metering units

Characteristic values	• Standard commercially available units are capable of handling up to 50 m^3 a day (the substrate receiving or holding vessel can be sized for a much larger capacity)
Suitability	• Usual silages, CCM, animal (including poultry) manure, bread waste, vegetables • Toothed rollers or bladed worm-type mixers are more suitable for long-fibre substances
Advantages	+ High throughput rates + Easy to fill with wheeled loaders or grabs + Large supply capacity for automatic control of comminution and feed + Robust equipment
Disadvantages	- Possibility of material forming bridges above the comminutor tool, although this tendency is heavily dependent on the shape of the receiving hopper and the type of substrate - If a breakdown occurs all the material has to be removed by manual means
Special considerations	• Paddle shafts reduce the risk of material forming bridges above the comminution tool
Designs	• Mobile fodder mixer with bladed worm-type vertical mixer for comminution • Receiving vessel with cutter discharge screw conveyors, sometimes bladed, for comminution and conveying • Receiving vessel with ripper paddle shafts for comminution and conveying • Receiving vessel with chipper-type conveyors/chipper gear for comminution and metering
Maintenance	• According to information supplied by the manufacturers, the equipment is of low-maintenance design. Maintenance contracts are available • It should be possible to carry out maintenance during the breaks in feeding

Wetting down to mash, homogenising

Substrates have to be wetted down to mash in the wet-digestion process to render them pumpable by increasing their water content, so that they can be pumped into the digester. This generally takes place in the pre-digester pit or other containers, just before the substrate is introduced into the digestion process. The liquid used for wetting down to mash is liquid manure, liquid digestate (from pressings), process water or – in exceptional cases – fresh water. Using liquid digestate can reduce fresh-water consumption. A further advantage is that even before it reaches the digester, the substrate is inoculated with seed bacteria from the digestion process. Consequently, this procedure can be applied to particularly good effect after hygienisation or in the process known as the plug flow process. The use of fresh water as make-up liquid should be avoided whenever possible, on account of the high costs involved. If water from cleaning processes is used as the make-up liquid for wetting down to mash, it has to be borne in mind that disinfectants can impede the digestion process because substances of this nature have a negative effect on the microorganism population inside the digester. The pump technology used for wetting down to mash is described in the section entitled 'Substrate transport and infeed'.

The homogeneity of the substrate is of major importance in terms of the stability of the digestion process. Severe fluctuations in loading and changes in substrate composition require the microorganisms to adapt to the variations in conditions, and this is generally linked to drops in gas yield. Pumpable substrates are usually homogenised by agitators in the pre-digester pit. However, homogenisation can also take place inside the

Table 3.4: Characteristic values and process parameters of external comminutors

Characteristic values	• Mills: low to midrange throughput rates (e.g. 1.5 t/h for a 30 kW machine) • Chippers: can also be set up for high throughput rates
Suitability	• Usual silages, CCM, cereals, grain maize (mill is generally adequate) • Potatoes, beets, green waste (mill, chipper)
Advantages	+ Easy accessibility to the equipment in the event of a breakdown + A supply of comminuted substrate can be prepared and kept ready + Filling can be automated and combined with receiving/holding units + Degree of comminution can be varied
Disadvantages	- Manual emptying is necessary if the machine becomes clogged or operation is disrupted in some other way - Relatively tolerant of interfering substances, but accelerated wear is possible
Special considera-tions	• Receiving vessels of various sizes can be installed • The height of the receiving vessel should be compatible with the machinery available on the farm
Designs	• Include beater mills, roller mills, chippers (mobile versions are also possible in principle)
Maintenance	• Can be arranged by contract with the manufacturer and is a necessity, depending on the substrates worked • A supply of comminuted material to bridge downtimes for maintenance can be stocked on site

Figure 3.7: Beater and roller mill for comminuting solid substrates [Huning Maschinenbau GmbH, DBFZ]

Table 3.5: Characteristic values and process parameters of comminution agitators in the pre-digester pit

Characteristic values	• Power draw: in the usual orders of magnitude for agitators, plus an allowance of 6 kW for agitators with 5-15 kW
Suitability	• Solid manure, foodstuff residues, prunings and clippings, straw
Advantages	+ Direct discharge of solids into the pre-digester pit + No further equipment needed
Disadvantages	- Dry matter content in the digester can be increased only up to the limit of the substrate's pumpability - Risk of layer of scum forming and also of sedimentation, depending on the substrate
Special considera-tions	• If solids are fed directly into the digester, e.g. by means of metering units, comminution agitators can also be used inside the digester
Designs	• Generally of the vane type fitted with cutters on the vanes, or with cutters on the agitator shaft
Maintenance	• Depending on the type of agitator, maintenance can be undertaken outside the pre-digester pit or the digester, without process interruption

Table 3.6: Characteristic values and process parameters of in-pipe comminution agitators

Characteristic values	• Perforated-plate comminutors up to 600 m^3/h delivery rate, motor power ratings between 1.1 and 15 kW • Inline twin-shaft comminutors based on rotary displacement pumps: comminution rates up to 350 m^3/h • Characteristic values depend heavily on dry matter content. Delivery rate drops off sharply as dry matter content increases.
Suitability	• Perforated-plate comminutors suitable for substrates with fibre content • Inline twin-shaft comminutors also suitable for pumpable substrates containing higher proportions of solids
Advantages	+ Easy accessibility to the equipment in the event of a breakdown + The units are easily opened and serviced in the event of clogging + Interfering substances are stopped by built-in separator trap (perforated-plate comminutor)
Disadvantages	- Dry matter content in the digester can be increased only up to the limit of pumpability of the substrate - Substrates containing interfering substances can cause accelerated wear (inline twin-shaft comminutor)
Special considerations	• Gate valves have to be installed so that the units can be isolated from the substrate pipe • Provision of a bypass controlled by a gate valve for use in the event of a breakdown can be practical • Achievable particle sizes can be determined by selection of the cutter or ripper technology
Designs	• Perforated-plate comminutor: rotary blades in front of strainer • Inline twin-shaft comminutor: shafts fitted with cutting or ripping tools
Maintenance	• Freestanding units can be serviced quickly without long outages • Easily accessible apertures significantly speed up cleaning

Figure 3.8: In-pipe substrate comminution (perforated-plate comminutor) [Hugo Vogelsang Maschinenbau GmbH]

digester, if different substrates are pumped in directly and/or are introduced into the digester via a solids infeed. The technology of the agitators is the subject of the section entitled 'Agitators'. Mixing in a pre-digester pit corresponds roughly to the systems of stirred-tank reactors (see Section 3.2.2.1, subsection entitled 'Process with full intermixing (stirred-tank reactors)').

Hygienisation

Compliance with statutory criteria for some substance groups that are critical from the epidemiological and phytohygienic standpoint can necessitate integrating thermal pretreatment into the biogas plant. Pretreatment consists of heating the substances to a temperature of 70 °C for at least one hour. Autoclaving is another method of killing germs. In this process the substrate is pretreated for 20 minutes at 133 °C and a pressure of 3 bar. This method is much less common in the sector than hygienisation at 70 °C, however. The size of the vessels used for hygienisation depends on throughput rate, and the same applies to energy input, so hygienically problematic co-substrates are generally hygienised before being fed into the digester. This is a simple way of ensuring that only the problematic substances are hygienised, so the hygienisation stage can be made more economical (partial-flow hygienisation). Full-flow hygienisation of all the feedstock or the pre-digested material is also possible. One advantage of pre-digester hygienisation is a certain degree of thermal decomposition of the substrate, which subsequently – and depending on its properties – is more readily fermentable.

Table 3.7: Characteristic values and process parameters of comminutors combined with conveyor technology in single units

Characteristic values	• Delivery rates up to 720 m^3/h possible • Discharge head up to max. 25 m • Power draw: 1.7–22 kW
Suitability	• Pumpable substrates containing long fibres
Advantages	+ Easy accessibility to the equipment in the event of a breakdown + The units are easily opened and serviced in the event of clogging + No further conveyor equipment needed
Disadvantages	- Dry matter content in the digester can be increased only up to the limit of the substrate's pumpability - Only a small proportion of the material flow can be comminuted. The proportion of comminuted matter can be increased by repeatedly returning the pumped matter to the comminutor
Special considerations	• Gate valves have to be installed so that the units can be isolated from the substrate pipe • Provision of a bypass controlled by a gate valve for use in the event of a breakdown can be practical • Achievable particle sizes can be determined by selection of the cutter or ripper technology
Designs	• Rotary pumps, impeller with cutting edges as dry-sited pump or submersible pump
Maintenance	• Freestanding pumps can be serviced quickly without long outages; submersible pumps are easily removed from the substrate for servicing • Maintenance apertures make for much shorter downtimes

Table 3.8: Characteristic values and process parameters of hygienisation tanks

Characteristic values	• Capacity: plant-specific, hygienisation tanks with 50 m^3 capacity, for example • Heating: internal or jacketed tanks • Duration: sizing must give due consideration to the filling, heating and emptying processes accompanying the one-hour dwell time for hygienisation (at 70 °C)
Suitability	• The substrate for conventional hygienisation vessels has to be pumpable, which means that it might have to be pretreated prior to hygienisation
Special considerations	• Instrumentation for logging the data of the hygienisation transient is essential • The hygienised substrate should not be transferred straight to the digester while still hot, because the biology in the digester cannot withstand the high temperatures (direct admixture might be possible in a plant with partial-flow fermentation) • The intermingling of hygienically problematic and hygienically acceptable material is unacceptable • Some substrates can be expected to entrain sand and dense materials
Designs	• Non-jacketed stainless-steel tanks within internal heating or jacketed stainless-steel tanks with in-wall heating or counterflow heat exchangers • Gastight and connected to a gas shuttle pipe or not gastight with expulsion air ducted out of the tank, via a waste-air purifier if necessary
Maintenance	• The tank must have at least one manhole • Comply with applicable health and safety regulations for working inside enclosed spaces (due consideration also has to be given to gas safety regulations) • The equipment as such (temperature sensors, agitators, pumps) has to be serviced; the tank itself should be maintenance-free

Hygienisation can be undertaken in airtight, heated stainless-steel tanks. Tanks of the conventional type for livestock fodder are often used. Hygienisation is monitored and documented by instrumentation for fill level, temperature and pressure. The post-hygienisation temperature of the substrate is higher than the process temperature prevailing inside the digester. Consequently, the hygienised substrate can preheat other substrates or it can be fed directly into and thus heat the digester. If there is no provision for utilising the waste heat of the hygienised substrate, suitable means must be used to cool it to the digester's temperature level. Figure 3.10 shows examples of hygienisation tanks; the specific properties of hygienisation tanks are summarised in Table 3.8.

Aerobic preliminary decomposition

In dry-digestion plants with garage-type digesters it is possible to integrate aeration of the substrate in preparation for the digestion process as such (see 3.2.2.1, 'Digester designs'). The composting processes caused by the introduction of air are associated with heating

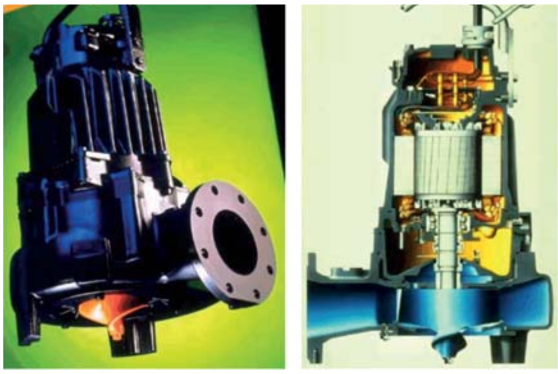

Figure 3.9: Submersible pump with cutting edges on the rotor as an example of a comminutor and pump combined in a single unit [ITT FLYGT Pumpen GmbH]

Figure 3.10: Hygienisation with recooling [TEWE Elektronic GmbH & Co. KG]

of the substrate to about 40 to 50 °C. Preliminary decomposition lasts for between two and four days; its advantages are incipient cell breakdown and spontaneous heating of the material, the results of which include less need for heating elements in the digester. On the negative side, however, organic substances have pre-reacted and are no longer available for the production of biogas.

Hydrolysis
A high organic loading rate in a single-phase process gives rise to the possibility of the process biology in the digester becoming imbalanced, in other words of acidogenesis progressing faster during primary and secondary digestion than acid degradation during methanogenesis [3-19]. High organic loading rate in combination with short dwell times also has a diminishing effect on substrate utilisation. Under worst-case conditions acidification can occur and the digester's biology collapses. This can be countered by siting hydrolysis and acidification processes in separate tanks upstream from the digester itself, or by creating a separate space inside the digester by means of special internals (e.g. two-phase digester). Hydrolysis can take place under aerobic and anaerobic conditions and works at pH values between 4.5 and 7. Temperatures from 25 to 35 °C generally suffice, but the temperature can be increased to 55 to 65 °C to increase the rate of reaction. The tanks can be holding tanks of various kinds (upright, horizontal) equipped with suitable agitators, heating elements and insulation, and so on. Feed to these tanks can be either continuous or batched. It is important to bear in mind that hydrolysis gas contains a large proportion of hydrogen. In a plant in aerobic operation with the hydrolysis gases venting to atmosphere, this can signify energy losses over the volume of biogas generated. There is also a safety problem involved, because hydrogen mixed with atmospheric air can form an explosive atmosphere.

Disintegration
Disintegration means the destruction of the cell-wall structure, permitting the release of all the cell material. This is one way of increasing the availability of the substrate to the microorganisms, accelerating the decomposition rates. Thermal, chemical, biochemical and physical/mechanical processes are used to promote cell breakdown. Possibilities include heating to < 100 °C at normal atmospheric pressure or > 100 °C under elevated pressure; hydrolysis as outlined above; adding enzymes; or utilising ultrasonic disintegration as one of the mechanical methods of encouraging cell decomposition. Discussion on the advantages of these processes is ongoing in the industry. On the one hand, the efficacy of the individual processes depends heavily on the substrate and its pretreatment, and on the other the processes invariably necessitate additional heat and/or electrical energy and this in turn has a direct effect on effectiveness in relation to the possible additional yield to be extracted from the plant. If integration of processes such as these is under consideration, planners should underpin the effective benefit of a disintegration stage for example by tests and additional analyses of the substrate to be used and through a cost/benefit study of the higher investment outlay vis-à-vis increase in earnings.

3.2.1.4 Transport and infeed

From the standpoint of process biology, a continuous flow of substrate through the biogas plant constitutes the ideal for a stable digestion process. It is virtually impossible to achieve this in practice, so quasi-continuous substrate feeding into the digester is the norm.

The substrate is added in a number of batches over the course of the day. Consequently, all the equipment needed for substrate transport is not in continuous operation. This is extremely important in terms of design.

The choice of technology for transporting and infeed depends primarily on the consistency of the substrate. A distinction has to be drawn between the technology for pumpable substrate and the technology for stackable substrate.

Substrate temperature has to be taken into account as far as infeed is concerned. Sizeable differences between material temperature and digester temperature (such as can occur in post-hygienisation infeed or when the digester is loaded during the winter) have a severe effect on process biology and this in turn can cause gas yield to diminish. Heat exchangers and heated pre-digester pits are two technical solutions adopted from time to time to counter these issues.

Transport of pumpable substrates

Pumps driven by electric motors are the most common means of transporting pumpable substrates in biogas plants. They can be controlled by timers or process-control computers, and in this way the overall process can be either fully or partially automated. In many instances, substrate transport 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 (e.g. feeding, complete emptying of tanks, breakdowns, etc.) are controlled by means of readily accessible or automatic gate valves. Figure 3.11 shows an example of pump siting and piping in a biogas plant.

Figure 3.11: Pumps in a biogas plant [WELtec BioPower GmbH]

It is important to make sure that pumps are readily accessible, with sufficient working space kept clear all-round. Even despite precautionary measures and good substrate pretreatment, pumps can still clog and need speedy clearing. Another point to bear in mind is that the moving parts of pumps are wear parts. Subject to harsh conditions in biogas plants, they have to be replaced from time to time without the necessity of shutting down the plant. Consequently, shut-off valves have to be installed so that the pumps can be isolated from the piping system for servicing. The pumps are virtually always of rotary or positive-displacement design, of the kind also used for pumping liquid manure.

Pump suitability in terms of power and delivery capability depends to a very large extent on the substrate, the degree of substrate preparation, and the dry matter content. Cutter or chopper comminutors and foreign-matter separators can be installed directly upstream to protect the pumps. Another possibility is to use pumps with pumping gear ready-tooled for comminution.

Rotary pumps

Rotary pumps are commonplace in liquid-manure pumping. They are eminently suitable for runny substrates. A rotary pump has an impeller turning inside a fixed body. The impeller accelerates the medium, and the resulting increase in flow velocity is converted into head or pressure at the rotary pump's discharge nozzle. The shape and size of the impeller can vary, depending on requirements. The cutter-impeller pump (see Figure 3.9) is a special kind of rotary pump. The impeller has hardened cutting edges designed to comminute the substrate. See Table 3.9 for characteristic values and process parameters.

Positive-displacement pumps

Positive-displacement pumps are used to pump semi-liquid substrates with high dry matter content. The speed of a positive-displacement pump can be varied to control delivery rate. This matches pump control more closely to precision metering of the substrate. The pressure stability of these self-priming pumps is better than that of rotary pumps, which means that delivery rate is much less dependent on head. Positive-displacement pumps are relatively susceptible to interfering substances, so it makes sense to install comminutors and foreign-matter separators to protect the pumps against coarse and fibrous constituents in the substrate.

Table 3.9: Characteristic values and process parameters of rotary pumps [3-1]

Characteristic values	• Pump pressure: up to 20 bar (in practice, pressure is usually lower) • Delivery rate from 2 m^3/min to 30 m^3/min • Power draw: e.g. 3 kW at 2 m^3/min, 15 kW at 6 m^3/min, heavily dependent on substrate • Generally for substrates with < 8% DM content
Suitability	• Runny substrates with low dry matter content; low proportions of straw are permissible
Advantages	+ Simple, compact and robust design + High delivery rate + Versatile (also usable as submersible pumps)
Disadvantages	- Not self-priming; so must be sited below the substrate grade level, for example in a shaft or pit - Not suitable for substrate metering
Special considerations	• Delivery rate is heavily dependent on pump pressure or head
Designs	• As submersible pump or for dry siting; also available as cutter pumps for comminution; submersible pumps available with drive below or above the substrate surface
Maintenance	• More difficult in the case of submersible pumps, although relatively easy access through removal apertures • Comply with applicable health and safety regulations for working inside the digester • Outages tend to be slightly longer than for other types of pump

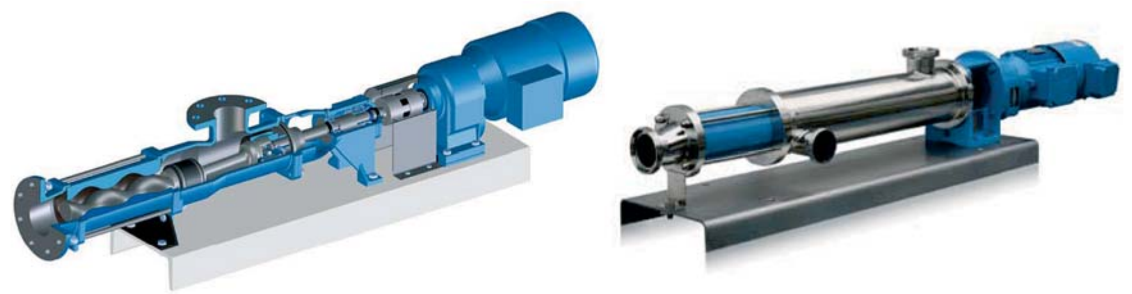

Figure 3.12: Eccentric single-rotor screw pump [LEWA HOV GmbH + Co KG]

Table 3.10: Characteristic values and process parameters of eccentric single-rotor screw pumps

Characteristic values	• Pump pressure: up to 48 bar • Delivery rate from 0.055 m^3/min to 8 m^3/min • Power draw: e.g. 7.5 kW at 0.5 m^3/min; 55 kW at 4 m^3/min; heavily dependent on substrate
Suitability	• Viscous pumpable substrates with low proportions of interfering substances and long-fibre substances
Advantages	+ Self-priming + Simple, robust design + Suitable for substrate metering + Reversible
Disadvantages	- Lower delivery rates than rotary pumps - Easily damaged by running dry - Easily affected by interfering substances (stones, long-fibre substances, pieces of metal)
Special considerations	• Delivery rate is severely dependent on viscosity; stable delivery despite fluctuations in pressure • Protection against running dry can be integrated • Very widespread use in wastewater treatment • The stator can usually be adjusted to suit delivery rate and substrate, and to compensate for wear • Reversible pumping direction available as special design
Designs	• As dry-sited pump
Maintenance	• Very durable • The design is inherently service-friendly; outages are short on account of the quick-change design of the screw drive

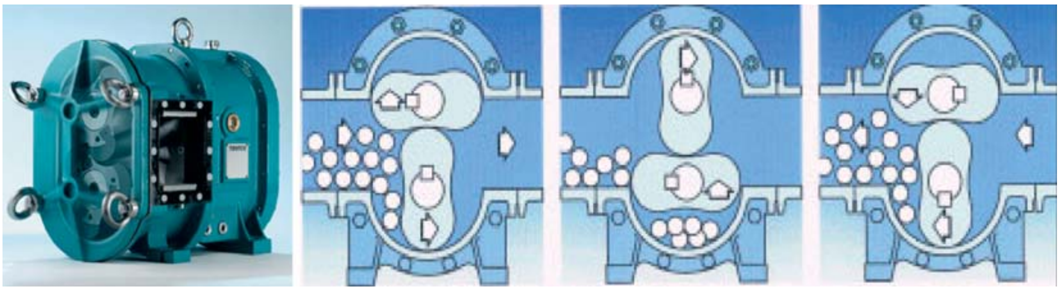

Figure 3.13: Rotary displacement pump (left), operating principle (right) [Börger GmbH (left), Vogelsang GmbH]

Table 3.11: Characteristic values and process parameters of rotary displacement pumps

Characteristic values	• Pump pressure: up to 12 bar • Delivery rate from 0.1 m^3/min to approx. 16 m^3/min • Power draw: approx. 2 to 55 kW
Suitability	• Viscous, pumpable substrates
Advantages	+ Simple, robust design + Self-priming up to 10 m water column + Suitable for substrate metering + Can pump coarser entrained matter and fibrous substances than eccentric single-rotor screw pumps + Not affected by dry running + Compact + Service-friendly + Reversibility is standard
Special considerations	• High rotary speeds up to 1300 rpm are good for performance optimisation • Adjustable half-liners optimise efficiency and durability by reducing play
Designs	• As dry-sited pump
Maintenance	• The design is inherently service-friendly; outages are short

Rotary-displacement pumps and eccentric single-rotor screw pumps are the most commonly used. **Eccentric single-rotor screw pumps** have a rotor shaped like a corkscrew running inside a stator made of an elastically resilient material. The action of the rotor produces an advancing space in which the substrate is transported. An example is shown in Figure 3.12. Characteristic values and process parameters are listed in Table 3.10.

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 of the pump. The medium is drawn in to fill the spaces on the suction side and is transported to the discharge side. Figure 3.13 illustrates the operating principle of the rotary displacement pump. See Table 3.11 for characteristic values and process parameters.

Transport of stackable substrates

The transport of stackable substrates is a feature of wet-digestion plants through to material infeed or to the stage of wetting down to mash with make-up liquid. Most of the work can be done with loaders of conventional design. It is only when automated feeding takes over that scraper-floor feeders, overhead pushers and screw conveyors are used. Scraper-floor feeders and overhead pushers are able to move virtually all stackable substrates horizontally or up slightly inclined planes. They cannot be used for metering, however. They permit very large holding tanks to be used. Screw conveyors can transport stackable substrates in virtually any direction. The only prerequisites are the absence of large stones and comminution of the substrate to the extent that it can be gripped by the worm and fits inside the turns of the worm's conveyor mechanism. Automatic feeder systems for stackable substrates are often combined with the loading equipment to form a single unit in the biogas plant.

Table 3.12: Characteristic values and process parameters of pre-digester pits

Characteristic values	• Made of water-impermeable concrete, usually reinforced concrete • Sized to buffer the quantity of substrate necessary for at least one or two process days
Suitability	• Pumpable, stirrable substrates • Also stackable substrates, if suitable comminutor technology is installed
Special considerations	• Good homogenisation and mixing of the substrates is possible • Settlement layers of stones can form • Provision must be made for removal of settlement layers by means of pump sump, collecting pit or scraper mechanisms • It is advisable to cover the pre-digester pit to control odour emissions • Solid matter in the infeed material can lead to clogging and the formation of scum and settlement layers
Designs	• Pits and tanks, round or rectangular, top flush with the ground or projecting above grade level, with wheel-loader accessibility to the filler • Pits sited higher than the digester have advantages, because the hydraulic differential can suffice to dispense with pumps • The technology for circulating the substrate can be the same as that used in the digesters
Maintenance	• If the design lacks provision for removing settlement layer material, this material has to be removed manually • Apart from this, virtually no maintenance outlay; maintenance of the various technical items of equipment is described in the corresponding sections

Figure 3.14: Pre-digester or receiving pit in feeding [Paterson, FNR; Hugo Vogelsang Maschinenbau GmbH]

Dry-digestion plants operating on the modular-box principle are commonplace: in these arrangements wheeled loaders are frequently the only means of transport required for the stackable substrate, or the boxes are filled directly from trailers with bottom scraper feeders or other, similar machines.

Infeed of pumpable substrates

Pumpable substrates are generally fed into the digester through sub-grade-level, concrete, substrate-nonpermeable pre-digester pits in which the liquid manure arisings are buffered and homogenised. Pre-digester pit sizing should enable the pit to buffer the quantities necessary for at least one or two process days. A farm's existing liquid-manure pits are frequently used for the purpose. If the biogas plant does not have separate provision for direct infeed of co-substrates, the pre-digester pit is where stackable substrates are also mixed, comminuted and homogenised, and if necessary mashed with make-up liquid to produce pumpable mixtures (cf. the subsection entitled 'Indirect feed through the pre-digester pit').The parameters of pre-digester pits are summarised in Table 3.12, Figure 3.14 shows an example.

Liquid (co-)substrates can also be pumped through a standardised tank adapter into the digester or a receiving tank of any suitable kind. Under these circumstances the receiving tanks must of course be technologically adapted to suit the properties of the substrate. Technical necessities in this respect can include, for example, chemically resistant tank materials, provision for heating, agitators and odour-controlling or gastight covers.

Infeed of stackable substrates

Solid matter can be fed into the digester either directly or indirectly. Indirect feed entails first introducing the stackable substrates into the pre-digester pit or into the substrate pipe to the digester (see Figure 3.15). Direct feed enables solid substrates to be loaded directly into the digester, bypassing the wetting down to mash with make-up liquid stage in the pre-digester pit or liquid-substrate pipe (see Figure 3.16). In this way co-digestates can be introduced independently of the liquid manure and at regular intervals [3-8]. Moreover, it is also possible to increase the dry matter content in the digester, thus increasing biogas productivity.

Indirect feed through the pre-digester pit

If the biogas plant does not have separate provision for direct infeed of co-substrates, the pre-digester pit is where stackable substrates are mixed, comminuted and homogenised, and if necessary mashed with make-up liquid to produce pumpable mixtures. This is the reason for equipping pre-digester pits with agitators, possibly combined with ripping and cutting tools for substrate comminution. If substrates containing interfering substances are processed, the pre-digester pit also functions as a separator for stones and settlement layers, which can be consolidated and removed by scraper-floor feeders and screw conveyors [3-3]. If the pre-digester is covered to stop odour emissions, the design of the cover should be such as not to hinder exposure of the pit for straightforward removal of settled matter.

Wheeled loaders or other mobile machines are used for filling, although automated solid-matter loading systems are also sometimes used. The mixture of solid matter and liquid is then transported into the digester by suitable pumps. The parameters of pre-digester pits are summarised in Table 3.12, Figure 3.14 shows an example.

Indirect feed into the piped liquid

As an alternative to infeed through a pre-digester pit, solid substrates such as biowaste, silage and solid manure can also be fed into the piped liquid by suitable metering devices such as hopper pumps (see Figure 3.17). The solid substrate can be forced into the liquid substrate pipe or the liquid flow can be piped directly through the solid-substrate hopper; infeed can also be accompanied by first-stage comminution of the substrate matter. The delivery rate of the infeed device can be adapted to suit DM content and the quantity of substrate to be added. The piped liquid can be liquid manure from a pre-digester pit/receiving vessel or substrate from the reactor or the digestate storage tanks. Systems of this nature are also used in midrange to large-scale biogas plants, because modular design guarantees a certain flexibility and a degree of safeguard against failure [3-17].

Table 3.13 summarises the most important characteristics of indirect feeding systems.

Direct feeding by ram

A feeding configuration with ram feeder uses hydraulic power to ram the substrates directly into the digester through an opening in the side, close to the bottom. Being injected close to the bottom in this way, the substrates are saturated in liquid manure and this reduces the risk of scum forming. The system has counter-rotating mixing augers that drop the substrates into the cylinder below, while also comminuting long-fibre substances [3-1]. The feeding system is generally linked to or installed directly underneath a receiving hopper. The characteristic values of ram feeders are summarised in Table 3.14, Figure 3.18 shows an example.

Direct feeding by screw conveyors

When loading screws are used for feeding, compacting screws force the substrate into the digester at a level below the surface of the liquid. This suffices to ensure that gas cannot escape from the digester through the screw winding. The simplest arrangement positions the metering unit on the digester, so only one vertical screw conveyor is needed for loading. All other configurations require upward screw conveyors to carry the substrate overhead above the digester. The screw conveyor intakes from any receiving container, and the receiving container itself can be fitted with comminuting tools [3-8]. Characteristic values of feeding systems with screw conveyors are summarised in Table 3.15; Figure 3.19 shows an example by way of illustration.

Mushing biomass

The co-digestates (e.g. beets) are comminuted to a pumpable consistency with the machines commonly used in beet processing. Residual dry matter content can be as high as 18%. The liquefied substrates are stored in suitable containers and are pumped directly into the digester, bypassing the pre-digester pit, by the units described in the 'Transport and infeed' section. This is a method of increasing dry matter content

Table 3.13: Characteristic values and process parameters of infeed screw conveyors

Characteristic values	• Material usually special steel; in closed housing • Infeed to digester: horizontal, vertical or angled down • Discharge just below surface of the liquid • Manual and automatic valves necessary, if digester fill level is above top of receiving hopper
Suitability	• All common stackable co-substrates, also freighted with stones smaller than the turns of the screw conveyor • Chopped substrates and long-fibre substrates can prove problematic
Advantages	+ Direction of transport is of no significance + Suitable for automation + Multiple digesters can be fed from one receiving hopper (e.g. with one upward-conveyor screw feeding to two separate compacting screws)
Disadvantages	- Abrasion in the screw-conveyor casings and at the screws - Sensitivity to largish stones and other interfering substances (depending on the size of screw turn)
Special considerations	• Can be used to transport substrates wetted down to mash • Escape of gas through the screw has to be prevented • Weight-based metering with screws is possible if the receiving hopper is fitted with suitable weighing equipment • Takes up space directly beside the digester • Hopper fill height above ground level and size of hopper opening must be matched to the farm's available loading equipment
Designs	• Compacting screw from receiving hopper conveying vertically, horizontally or diagonally to the digester • Upward-conveyor screw to lift substrate overhead (vertical transport) • Versatility for combination with receiving systems of various kinds (e.g. hopper, scraper-bottom container, fodder-mixer trailer)
Maintenance	• Moving parts, so outlay for regular servicing must be taken duly into account • Manual intervention required to clear clogging or remove trapped interfering substances • Servicing of the screw that feeds to the digester necessitates what can be considerable downtime

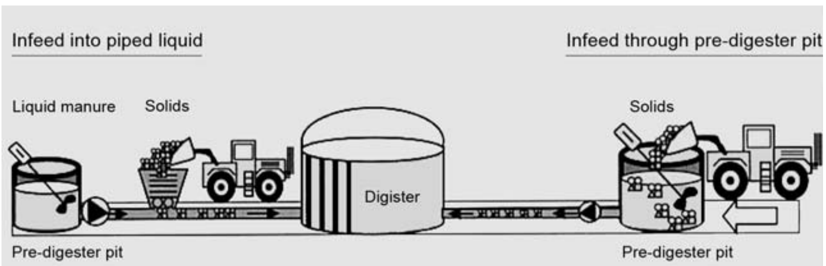

Figure 3.15: Indirect solids infeed (schematic) [3-1]

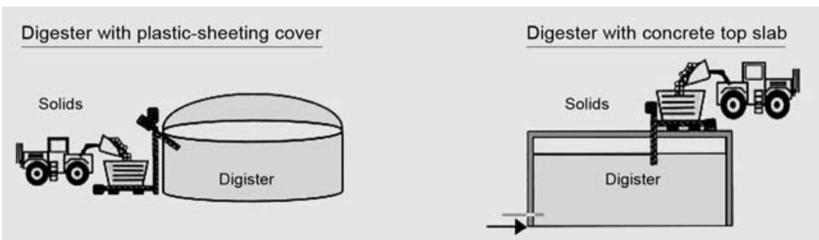

Figure 3.16: Direct solids infeed (schematic) [3-1]

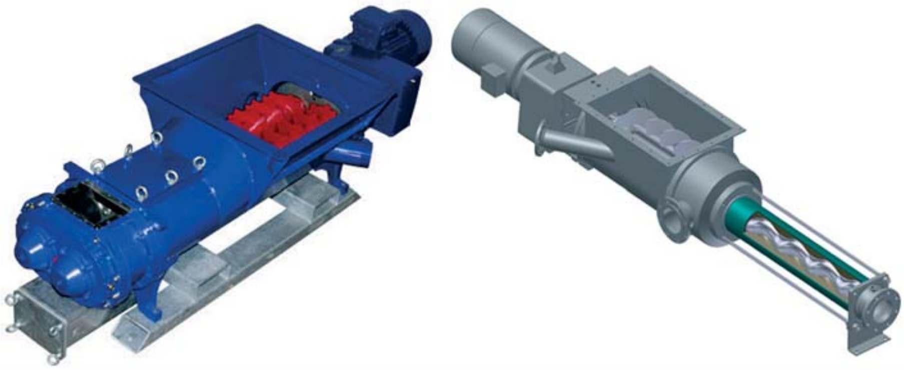

Figure 3.17: Hopper pumps with integrated rotary displacement pump (left) and eccentric single-rotor screw pump (right) [Hugo Vogelsang Maschinenbau GmbH (left), Netzsch Mohnopumpen GmbH]

Table 3.14: Properties of hopper pumps for solids infeed into piped liquid

Characteristic values	• Pump pressure: up to 48 bar • Delivery rate, suspension: 0.5-1.1 m^3/min (depending on type of pump and the pumped suspension) • Delivery rate, solids: approx. 4-12 t/h (twin-shaft worm feed with comminution)
Suitability	• Suitable for pre-comminuted substrates to a very large extent free of interfering substances
Advantages	+ High suction and discharge capacities + Robust design, available with wear protection in some cases + Suitable for metering + Comminution by ripper tooling of the feeder worm conveyors
Disadvantages	- In some cases affected by interfering substances (stones, long-fibre substances, pieces of metal)
Special considerations	• Comminution, mixing and wetting down to mash possible in a single step • Any method of transporting the solid matter is possible (wheeled loader, conveyor, receiving/holding units) • Liquid phase feed is by separate pump
Designs	• As dry-sited unit • Single-shaft or twin-shaft worm feed of the substrates to the piped liquid/to the pump unit, conveyor screws partly toothed for substrate comminution • Preferred types of pump: rotary displacement pumps and eccentric single-rotor screw pumps, sometimes integrated into hopper pump
Maintenance	• The design is inherently service-friendly; outages are short

Figure 3.18: Infeed of stackable biomass into the digester with ram feeder [PlanET Biogastechnik GmbH]

Table 3.15: Characteristic values and process parameters of ram feeders

Characteristic values	• Material usually special steel; closed housing for the feeder ram • Feed into digester: horizontal, infeed at bottom of digester possible • Manual and automatic valves necessary, if digester fill level is above top of receiving hopper
Suitability	• All common stackable co-substrates, including long-fibre substrates and substrates freighted with stones, given suitable worm-conveyor design
Advantages	+ Largely odourless + Very good metering capability + Suitable for automation
Disadvantages	- Risk of settlement layer formation in the digester if the ram-fed substrate clumps, so sub-optimum accessibility for microorganisms in the digester - Only horizontal feed of the substrate is possible - Only one digester can be fed from the receiving hopper
Special considera-tions	• Infeed adapter must be sealed to prevent passage of liquid • Hopper fill height above ground level and size of hopper opening must be matched to the farm's available loading equipment • Crossed blading to break up the ram plug is offered as an option by the manufacturer and would appear extremely practical, on account of the risk of the substrate clumping • Takes up space directly beside the digesterg • Weight-based metering with ram feed is possible if the receiving hopper is fitted with suitable weighing equipment
Designs	• Hydraulic ram with worm conveyors powered either hydraulically or electrically • Versatility for combination with receiving systems of various kinds (e.g. hopper, scraper-bottom container, fodder-mixer trailer)
Maintenance	• Moving parts, so outlay for regular servicing must be taken duly into account • Servicing of the ram feeder necessitates what can be considerable downtime, possibly also associated with emptying of the digester

Figure 3.19: Feeding stackable biomass into the digester with screw conveyors [DBFZ]

in a digester operating with liquid manure as base substrate [3-8].

Sluices

Sluices are a very robust and straightforward solution for substrate infeed. They are easily filled by wheeled loaders and they also allow large amounts of substrate to be added very rapidly. This infeed technique is still to be found in older, small-scale plants. It is very inexpensive and in principle it requires no maintenance. Its direct connection to the digester, however, can give rise to considerable odour-nuisance problems and allow methane to escape from the digester, so as a technique it no longer features in the construction of new plants [3-17].

Infeed of stackable substrates in dry digestion (garage-type digesters)

The box-type digesters are easily accessible to wheeled vehicles, so the plants in operation have no

Table 3.16: Characteristic values of valves, fittings and piping for liquid-retaining pipes

Characteristic values	• Pipe material: PVC, HDPE, steel or special steel, depending on medium load and pressure level • Connections of flanged, welded or glued design • The diameter of pressurised pipes should be 150 mm; pipes that are not under pressure (overflow and return pipes) should be 200–300 mm in diameter, depending on the substrate • All materials must be chemically resistant to the substrate and must be rated for maximum pump pressure (pressurised piping)
Special considerations	• Wedge gate valves form a very good seal, but they are easily fouled by interfering substances • Blade-type gate valves slice through fibrous substances • Ball-head quick-action locking mechanisms should be used for pipes that have to be disconnected quickly • All valves, fittings and pipes must be suitably protected against frost; suitable insulation has to be fitted for handling warm substrate • Always run pipes at 1-2% of fall, to permit easy emptying • Route the piping accordingly to prevent backflow of substrate from the digester to the pre-digester pit • When laying pipes underground, make sure that the subbase is well compacted before the pipework is installed • Install a gate valve upstream of each flap trap, in case interfering substances prevent the flap trap from closing correctly. • Cast iron piping is not a good choice, because the formation of deposits is more of a consideration than in smooth-surfaced plastic pipes, for example

Table 3.17: Characteristic values of valves, fittings and piping for gas-retaining pipes

Characteristic values	• Pipe material: HDPE, PVC, steel or special steel (no piping in copper or other non-ferrous metals) • Connections of flanged, welded, glued or threaded design
Special considerations	• All valves, fittings and pipes must be suitably protected against frost • Always route piping runs with a constant fall to prevent unwanted build-up of condensate (risk of clogging) • All gas-retaining pipes must have suitable provision for condensate draining; dewatering via condensate duct • All valves and fittings must be readily accessible, easily serviced and easily worked by an operator adopting a safe stance • When laying pipes underground, make sure that the subbase is well compacted before the pipework is installed and make sure that the entire pipework is free of stresses and strains; if necessary, include bellows adapters or U-bends

provision for automated feed. Both feeding and emptying are undertaken using conventional agricultural transport equipment, generally wheeled loaders.

Valves, fittings and piping

The valves, fittings and piping must be medium-proof and corrosion-resistant. Valves and fittings such as couplers, shut-off gate valves, flap traps, cleaning ports and pressure gauges must be readily accessible and operable and they must also be installed in such a way as to be safe from frost damage. The 'Sicherheitsregeln für Biogasanlagen' (Safety Rules for Biogas Systems) issued by the Bundesverband der landwirtschaftlichen Berufsgenossenschaften (German Agricultural Occupational Health and Safety Agency) contain information about the regulations for piping, valves and fittings and can be of assistance in achieving compliance with the laws and engineering codes with regard to material properties, safety precautions and leak tests for safe operation of the biogas plant [3-18]. One factor that has proved extremely important is the necessity of providing suitable means of removing condensate from all piping runs, without exception, or of running the pipes with enough fall to ensure that slight settling or sag cannot produce unintended high points along the runs. On account of the low pressures in the system, very small quantities of condensate can suffice to cause a complete blockage. The most important parameters for liquid-retaining pipes and gas-retaining pipes are summarised in Tables 3.16 and 3.17, respectively. Figures 3.20 and 3.21 show examples by way of illustration.

3.2.2 Biogas recovery

3.2.2.1 Digester designs

The links between digester design and the fermentation process are close. Substrate fermentation can be

Figure 3.20: Pipes, valves and fittings in a pump station, shut-off gate valves [DBFZ]

Figure 3.21: Working platform between two tanks with piping and pressure-relief devices (left); gas pipe with compressor blower (right) [MT-Energie GmbH (left), DBFZ (right)]

achieved by processes with full intermixing (stirred-tank reactors), plug-flow processes or special processes.

Process with full intermixing (stirred-tank reactors)

Cylindrical, upright stirred-tank reactors are used primarily in agricultural plants for biogas production. At this time (2009), this type accounts for about 90% of the installed base. The digester consists of a tank with concrete bottom and sides made of steel or reinforced concrete. The tank can be sited either completely or partly sub-grade, or above ground.

The cover on top of the tank is gastight, though the design specifics can vary depending on requirements and mode of construction. Concrete covers and plastic sheeting are the most common. The substrate is stirred by agitators sited in or beside the reactor. The specific properties are listed in Table 3.18, Figure 3.22 shows a section through a reactor of this kind. The different kinds of agitator are discussed in more detail in Section 3.2.2.3.

Plug-flow process

Biogas plants with plug flow – the wet-digestion version is also known as a tank through-flow arrangement – use the expeller effect of fresh substrate infeed to create a plug flow through a digester of round or box section. Mixing transverse to the direction of flow is usually achieved by paddle shafts or specially designed baffles. Table 3.19 lists the characteristic properties of this type of plant.

Broadly speaking, there are horizontal and upright plug-flow digesters. Virtually all the digesters used in agricultural plants are of the horizontal type. At this time, upright digesters operating on the plug-flow principle are rare and they are not considered in this study. Examples for wet digestion and dry digestion are illustrated in schematic form in Figures 3.23 to 3.25.

The digesters are usually horizontal steel tanks, factory-built and then delivered to site. This necessitates transport of the digesters to site, which is possible only up to a certain size of tank. Possible uses are

Table 3.18: Properties of stirred-tank biogas reactors; as described in [3-1] and [3-3]

Characteristic values	• Sizes in excess of 6,000 m^3 possible, but intermixing and process control become more complex as size increases • Generally made of concrete or steel
Suitability	• In principle for all types of substrate, preferably pumpable substrates with low and midrange dry matter content • Stirring and conveying equipment must be adapted to the substrate • Return of digestate if feed is pure energy crop • Suitable for continuous, quasi-continuous and intermittent feeding
Advantages	+ Design is cost-effective when reactor volume is in excess of 300 m^3 + Variable operation in through-flow or through-flow/buffer-tank configurations + Depending on design, the equipment can usually be serviced without the digester being emptied
Disadvantages	- Flow short-circuits are possible and likely, so dwell time cannot be stated with assurance - Scum and settlement layers can form
Special considerations	• Sediment removal is recommended for some substrates (e.g. poultry droppings on account of lime sediment), scraper floor with screw discharge conveyor
Designs	• Upright cylindrical tank either above ground or top flush with grade level • The intermixing equipment must be very powerful; if only liquid manure is fermented in the digester pneumatic circulation by the injection of biogas is viable • Means of recirculation: submersible-motor agitators sited at positions inside the reactor's enclosed space, axial agitator in a central vertical duct, hydraulic recirculation with external pumps, pneumatic recirculation by injection of biogas in a vertical duct, pneumatic recirculation by large-area biogas injection through nozzles at the bottom of the reactor
Maintenance	• Manhole facilitates accessibility

Table 3.19: Properties of biogas reactors with plug flow; as described in [3-1] and [3-3]

Characteristic values	• Size: horizontal digesters up to 800 m^3, upright digesters up to approx. 2500 m^3 • Material: primarily steel and special steel, also reinforced concrete
Suitability	• Wet digestion: suitable for pumpable substrates with high dry matter content • Dry digestion: stirring and conveying equipment must be adapted to the substrate • Designed for quasi-continuous or continuous feeding
Advantages	+ Compact, cost-effective design for small-scale plants + Separation of the digestion stages in the plug flow + Design eliminates the formation of scum and settlement layers + Dwell times are as predicted because design largely prevents flow short-circuits + Short dwell times + Can be heated effectively; the compact design helps minimise heat losses + Wet digestion: powerful, reliable and energy-saving agitators can be used
Disadvantages	- Space needed for the tanks - No inoculation of the fresh material or inoculation must be done by return of digestate as seed material - Economical only when on small scale - The reactor has to be fully emptied if the agitator requires servicing
Designs	• As plug-flow reactors with round or box cross-section • Can be horizontal or vertical, but horizontal is the norm • In an upright reactor the plug flow is usually established by vertical internals, rarely by horizontal internals • Can be operated with or without intermixing equipment
Special considerations	• Openings must be provided for all the devices and pipes requiring connection • A blow-off valve for the gas chamber has to be installed for safety
Maintenance	• At least one manhole is necessary so that the interior of the reactor can be accessed in the event of a breakdown • Comply with applicable health and safety regulations for working inside the digester

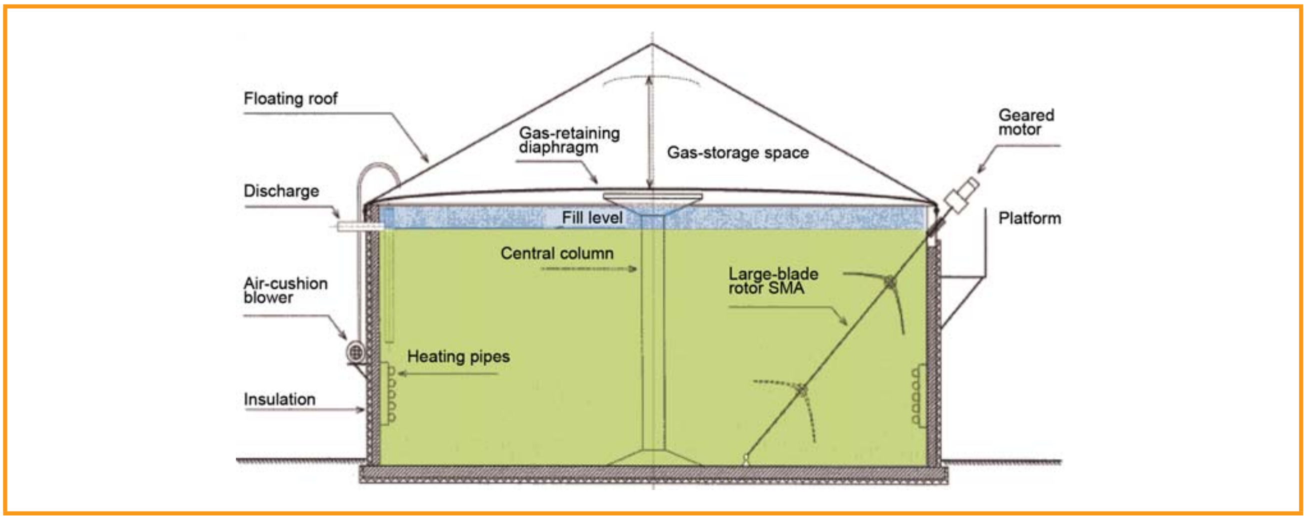

Figure 3.22: Stirred-tank reactor with long-shaft agitator and other internals [Anlagen- und Apparatebau Lüthe GmbH]

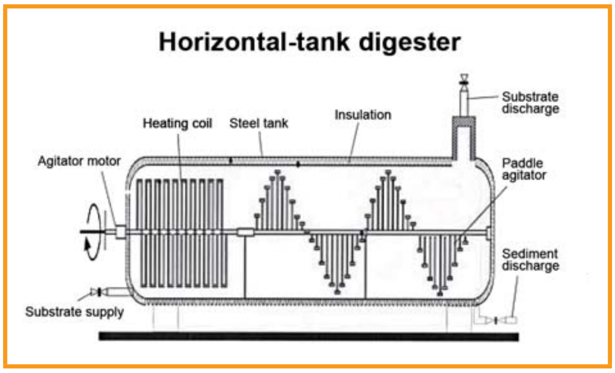

Figure 3.23: Plug-flow reactor (wet digestion) [3-4]

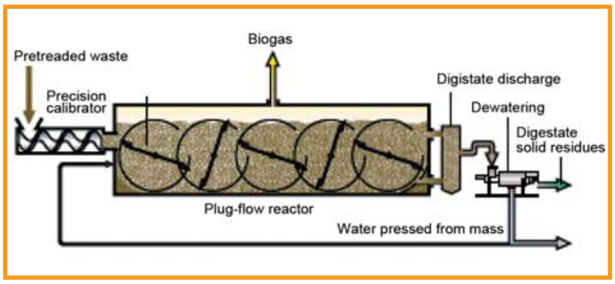

Figure 3.24: Plug-flow reactor (dry digestion) [Strabag-Umweltanlagen]

as main digesters for small-scale plants or as preliminary digesters for larger plants with stirred-tank reactors (round tanks). Horizontal digesters arranged in batteries for parallel operation can increase throughput.

The plug-flow principle reduces the possibility of unintentionally discharging undigested substrate from the reactor, and dwell time can be maintained very reliably for all the material [3-3].

Batch processes

Batch processes use mobile containers or stationary box-type digesters. These processes have achieved commercial maturity in recent years and are established on the market. Reinforced-concrete box digesters are particularly common for fermenting bulk substrates such as maize and grass silage.

In the batch process the digesters are filled with biomass and sealed airtight. The microorganisms in the seed substrate mixed through the fresh substrate to inoculate it heat the substrate in the first phase, in which air is fed into the digester. A composting process associated with the release of heat takes place. When the biomass reaches operating temperature, the supply of air is shut off. Once the supply of entrained oxygen has been consumed, microorganisms become active and convert the biomass into biogas as in wet digestion. The biogas is trapped in the gas headers connected to the digester and piped off for energy extraction [3-1].

Batteries with between 2 and 8 boxes have proved practical, and the most common arrangement is a 4-box battery. This arrangement suffices to achieve quasi-continuous gas production.

A digester battery should also have a leachate tank to catch the seepage liquid from the reactors so that it too can be converted into biogas. The leachate is also sprinkled over the fermentation mass in the reactor to inoculate the material. An example of a box-type digester battery is shown in Figure 3.26.

Special processes

Apart from the very common processes for wet digestion and dry digestion as described above, there are

Figure 3.25: Plug-flow reactors; field examples, cylindrical (left), box section, with overhead gas reservoir (right) [Novatech GmbH (left), DBFZ (right)]

Figure 3.26: Examples of box digesters; digester battery [Weiland, vTI] and box-digester door [Paterson, FNR]

other processes that are not adequately classifiable in these categories. Several new approaches have emerged, but at this time their future significance cannot be gauged.

Special processes of wet digestion in widespread use in the eastern part of Germany use a two-chamber method of mixing the substrate (the 'Pfefferkorn' process, named after the inventor who developed the principle). In a digester of this nature the substrate is recirculated hydraulically by automatic pressure build-up resulting from gas production and pressure blow-down when a predefined gauge pressure is achieved. This means that no electricity is necessary for stirring. The drawback is that the digester is more complex in terms of structural design. In the agricultural sector more than 50 biogas plants based on this technology have been built, with digester capacities between 400 and 6000 m^3, primarily for liquid-manure digestion with low energy-crop content and for sewage-sludge digestion. Figure 3.27 is a cutaway view of a two-chamber digester.

Figure 3.27: Two-chamber digester [ENTEC Environment Technology Umwelttechnik GmbH]

Various special adaptations of batch-principle dry digestion have also emerged. Notwithstanding the differences, common to all these designs is a closed space for bulk substrates.

Plastic-tunnel digestion is a very straightforward solution that has evolved from silage technology. A gastight plastic tunnel up to 100 metres long set on a heatable concrete slab is filled with feedstock. The biogas is taken off by an integral header and piped to a CHP unit.

A system with overhead loading is known as a sequential batch reactor (SBR). The substrate is wetted only by periodic percolation until the feedstock is immersed in liquid.

A new development is two-stage digestion in stirred box digesters. Worm shafts inside the digesters homogenise the material, screw conveyors carry it to the next stage. The batch digesters are doorless. Instead, the bulk feedstock is fed in and discharged by full-encapsulation screw conveyors.

A two-stage dry/wet digestion process requires a box chamber for hydrolysis and leaching of the feedstock The liquid from hydrolysis and leaching is piped to a hydrolysis tank. This tank feeds to the methanisation stage. The process is capable of starting and stopping methanisation within a few hours and is therefore suitable for integration into gross dependable capacity supply. See Figure 3.28 for an overview of the special designs.

3.2.2.2 Structure of digesters

In general terms, digesters consist of the digestion tank as such, which is thermally insulated, plus a heating system, mixer systems and discharge systems for sediments and the spent substrate.

Tank design

Digester tanks are made of steel, special steel, or reinforced concrete.

Reinforced concrete is rendered sufficiently gastight by water saturation. The moisture required for this purpose is contained in the substrate and the biogas. The digesters are cast on site using cast-in-place (CIP) concrete or assembled from prefabricated parts or precastings. Concrete tanks can be sited partly or entirely sub-grade, if the subsoil conditions are suitable. The tank cover can be made of concrete and the concrete tops of sub-grade tanks can be rated to carry vehicular traffic, with the biogas stored separately in an external gas storage tank. Digesters also designed for gas storage have gastight tops made of heavy-gauge plastic sheeting. As of a certain tank size a central column is necessary to support the weight of a concrete top slab. If the work is not to professional standard there is a risk of the top slab cracking. In the past cracking, leaks and concrete corrosion were not uncommon, and in extreme cases digesters affected by these problems have had to be demolished.

The use of high-grade concrete and professional planning of the digesters are essential to avoid problems of this nature. The Bundesverband der Deutschen Zementindustrie e. V. (Federal Association of the German Cement Industry) has issued its LB 14 set of instructions for the agricultural construction sector entitled 'Beton für Behälter in Biogasanlagen' (Concrete for tanks in biogas plants) [3-13]. This set of instructions contains the association's recommendations relating to the requirements applicable to the quality of concrete used in reinforced-concrete digesters. The key performance indicators for the use of concrete in the construction of biogas plants are outlined in Table 3.20. Additional information is set out in the cement industry association's instructions for the agricultural construction sector LB 3 [3-10] and LB 13 [3-11]. Figure 3.29 shows a reinforced-concrete digester under construction.

Tanks made of **steel and special steel** are set on concrete foundations, to which they are connected. Coiled sheet metal strip and welded or bolted steel plates are used. The bolted joins must be adequately sealed. Steel digesters are always of above-ground design. In most instances the roof structure is utilised for gas storage and gastight heavy-gauge plastic sheeting is used. Characteristic values and properties of steel tanks are listed in Table 3.21. Examples are shown in Figure 3.30.

3.2.2.3 Mixing and stirring

There are several reasons why it is important to ensure that the contents of the digester are thoroughly mixed:

- inoculation of fresh substrate by contact with seed material in the form of biologically active digester fluid;
- uniform distribution of heat and nutrients inside the digester;
- prevention of settlement and scum layers, and the breaking up of these layers if they have the opportunity to form;
- good degassing of the biogas from the substrate.

The fermenting substrate is minimally mixed by the introduction of fresh substrate, by thermal convective flows and by gas bubbles rising through the fermenting mass. This passive mixing, however, is not enough, so the mixing process has to be actively assisted.

Mixing can be done mechanically by systems such as agitators inside the reactor, hydraulically by pumps sited in close proximity outside the digester, or pneumatically by blowing biogas into the tank.

Figure 3.28: Examples of special constructions in dry digestion; sequential batch reactor (left), stirred-tank box digester (centre), methanisation stage of the dry/wet digestion process and external gas storage tank (right) [ATB Potsdam (left), Mineralit GmbH (centre), GICON GmbH (right)]

Figure 3.29: A concrete digester under construction [Johann Wolf GmbH & Co Systembau KG]

The last two of these methods are of lesser significance. In Germany, mechanical mixers or agitators are used in about 85 to 90% of plants [3-1].

Mechanical mixing

The substrate is mechanically mixed by agitators. A distinction can be drawn between shear-action and kneading agitators. Viscosity and dry matter content of the medium are the definitive factors regarding the type of agitator used. Combinations of the two are not uncommon. They interwork for better effect.

The agitators operate continuously or intermittently. Practice has shown that the stirring intervals have to be optimised empirically on a case-to-case basis to suit the specifics of the biogas plant, which include the properties of the substrate, digester size, tendency of scum to form, and so on. For safety's sake it is best to stir more frequently and for longer periods of time after plant startup. The accruing wealth of experience can be used to optimise the duration and frequency of intervals and the settings of the agitators. Different types of agitator can be used for the purpose.

Submersible-motor agitators (SMA) are frequently used in upright digesters operating on the stirred-tank principle. A distinction is drawn between high-speed SMAs with two- or three-blade propellers and low-speed SMAs with two large rotor blades. These shear-action agitators can be driven by gearless and geared electric motors. They are completely submerged in the substrate, so their housings have to be jacketed for pressure-watertightness and corrosion resistance, and in this way they are cooled by the surrounding medium [3-1]. Characteristic values for submersed-motor propeller-type agitators are listed in Table 3.22, and Figure 3.31 shows examples.

Alternative siting for the motor of a shear-based **long-shaft agitator** is at the end of an agitator shaft slanting through the digester. The motor is outside the digester, with the shaft passing through a gastight gland in the digester top slab or at a point in the side wall close to the top in the case of a reactor with plastic-sheeting cover. The shafts can be supported by extra bearers on the base of the digester and fitted with one or more small-diameter propellers or large-diameter agitators. Table 3.23 contains characteristic values of long-shaft agitators, Figure 3.32 shows some examples.

Axial agitators are another means of achieving shear-based mechanical mixing of the substrate inside the digester. They are commonplace in biogas plants in Denmark and operate continuously. They rotate on a shaft usually dropped from the centre of the digester roof. The input speed from the drive motor, mounted outside the digester, is geared down to no more than a few revolutions per minute. These agitators are designed to create a constant flow inside the digester, the direction of circulation being downward close to the centre and upward at the sides. Characteristic values and process parameters of axial agitators are summarised in Table 3.24, and an example is shown in Figure 3.33.

Table 3.20: Characteristic values and process parameters of concrete for tanks in biogas plants; [3-10], [3-11], [3-13]

Characteristic values	• For digesters in the liquid-wetted space C25/30; in the gas space C35/45 or C30/37 (LP) for components with frost exposure, for pre-digester pits and liquid-manure ponds = C 25 • If suitable means of protecting the concrete are implemented, a lower minimum strength of the concrete is possible • Water-cement ratio = 0.5, for pre-digester pits and liquid-manure ponds = 0.6 • Crack-width limitation by computation is = 0.15 mm • Concrete coverage over reinforcement, minimum inside 4 cm
Suitability	• For all types of digester (horizontal and upright) and pits
Advantages	+ Foundation and digester can be a single structural component + Assembly from precastings partly possible
Disadvantages	- Concreting can be undertaken only during frost-free periods - Construction time is longer than for steel reactors - Considerable difficulty is involved if post-construction openings have to be made
Special considerations	• If heating elements are installed in the concrete base slab, provision has to be made for thermally induced stresses and strains • The structure must be dependably gastight • In order to avoid damage, the reinforcement has to be designed to take the stresses and strains resulting from what are sometimes considerable temperature deltas in the structure • In particular, the concrete surfaces not continuously covered by substrate (gas space) must be coated (e.g. with epoxide) to protect them against acid attack • The authorities often require installation of a leak detection system • Sulphate resistance must be ensured (use of high-sulphate-resistance cement, HS cement) • Consequently, the structural analysis for planning of the digester tank or tanks has to be very thorough and specific to the site, in order to prevent cracks and damage

Table 3.21: Characteristic values and process parameters of steel for tanks in biogas plants

Characteristic values	• Galvanised/enamelled structural steel St 37 or special steel V2A, in the corrosive gas space V4A
Suitability	• For all horizontal and upright digesters and for pits
Advantages	+ Prefabrication and short construction periods possible + Flexibility for making openings
Disadvantages	- The foundation can be cast only in frost-free periods - Some extra means of support is generally needed for agitators
Special considerations	• In particular the surfaces not constantly immersed in substrate (gas space) have to be made of higher-grade material or have a suitable protective coating applied in order to prevent corrosion • The entire structure must be gastight, particularly the connections at the foundation and the roof • The authorities often require installation of a leak detection system • It is absolutely essential to avoid damaging the protective coatings of structural-steel tanks


Figure 3.30: A special-steel digester under construction [Anlagen- und Apparatebau Lüthe GmbH]

Table 3.22: Characteristic values and process parameters of submerged-motor propeller-type agitators; [3-2], [3-16], [3-17]

Characteristic values	*General:* • Working time depends on the substrate; has to be determined during the plant shakedown phase • Two or more agitators can be installed in large digesters *Propeller:* • High-speed, intermittent operation (500 to 1500 rpm) • Power range: up to 35 kW *Large-blade rotor:* • Slow-speed, intermittent operation (50 to 120 rpm) • Power range: up to 20 kW
Suitability	• All substrates in wet digestion, in upright digesters • Not suitable for extremely high viscosities
Advantages	*Propeller:* + Creates turbulent flow, so very good intermixing in the digester and break-up of scum and settlement layers can be achieved + Movability is very good, so selective intermixing in all parts of the digester possible *Large-blade rotor:* + Very good intermixing in the digester can be achieved + Produces less turbulent flow, but higher shear action per consumed kW_{el} by comparison with high-speed SMAs
Disadvantages	*General:* - On account of guide rails, many moving parts inside the digester - Servicing necessitates opening of the digester, although emptying is not usually necessary (if winch installed) - Settling and scum formation possible on account of intermittent mixing *Propeller:* - Cavitation possible in substrates rich in dry matter (agitator 'spins in its own juice') *Large-blade rotor:* - Orientation of the agitator has to be set before initial startup
Special considera-tions	• The glands taking the guide tubes through the top slab of the digester must be gastight • Intermittent operation control by timers, for example, or some other appropriate means of process control • Motor casing must be completely sealed against liquid; automatic leak detection inside the motor casing is available from some manufacturers • Motor cooling must be reliably maintained even despite high digester temperatures • Soft start and variable speed control possible with frequency converters
Designs	*Propeller:* • Submersible gearless or reduction-geared electric motors with propeller • Propeller diameters up to approx. 2.0 m • Material: corrosion-proof, special steel or coated cast iron *Large-blade rotor:* • Submersible gearless or reduction-geared electric motors with two-blade rotor • Rotor diameter: from 1.4 to 2.5 m • Material: corrosion-resistant, special steel or coated cast iron, blades made of plastic or glass-fibre-reinforced epoxy resin
Maintenance	• In some cases difficult, because the motor has to be lifted out of the digester • Maintenance hatches and engine-extraction hatches have to be integrated into the digester • Comply with applicable health and safety regulations for working inside the digester

Paddle (or paddle-wheel) agitators are low-speed, long-shaft stirrers. The stirring effect is achieved not by shear action but by kneading the substrate, and good mixing is claimed for substrates with a very high dry matter content. These agitators are used in upright stirred-tank reactors and in horizontal digesters of plug-flow design.

In *horizontal* digesters the agitator shaft is of necessity horizontal. This shaft carries the paddles that stir the substrate. The horizontal plug flow is maintained by batched infeed of fresh material into the digester. The agitators often have heating coils integrated into the shafts and the stirrer arms (see Figure 3.23) to heat the substrate. The agitator operates for short periods at low speed several times a day. The characteristic values are listed in Table 3.25.

Table 3.23: Characteristic values and process parameters of long-shaft agitators

Characteristic values	*Propeller:* • Medium- to high-speed (100–300 rpm) • Available power range: up to 30 kW *Large-blade rotor:* • Low-speed (10–50 rpm) • Available power range: 2–30 kW *General:* • Working time and speed depend on the substrate; have to be determined during the plant shakedown phase • Material: corrosion-resistant, coated steel, special steel
Suitability	• All substrates in wet digestion, only in upright digesters
Advantages	+ Very good intermixing in the digester can be achieved + Virtually no moving parts inside the digester + Drive is maintenance-free outside the digester + If operation is continuous, can prevent the formation of settlement and scumming
Disadvantages	- Siting is stationary, so risk of incomplete mixing - Consequently, possibility of scum and settlement layers forming in parts of the digester - Settling and scum formation possible if mixing is intermittent - Motors sited outside the tank can give rise to problems on account of noise nuisance from motor and gearing - The bearings and shafts inside the digester are susceptible to faults; if problems arise it can be necessary to partially or completely empty the digester
Special considerations	• Glands carrying the agitator shaft must be gastight • Intermittent operation control by timers, for example, or some other appropriate means of process control • Soft start and variable speed control possible with frequency converters
Designs	• Out-of-tank electric motors with/without gearing, in-tank agitator shaft with one or more propellers or two-blade rotors (also if applicable tooled for comminution, see the section headed 'Comminution') • In some cases end of shaft in bearer on bottom of digester, floating or swivel-mounted • Adapter for PTO drive possible
Maintenance	• Motor maintenance is straightforward on account of siting outside the digester; no need to interrupt the process • Repairs to propeller and shaft difficult, because they have to be taken out of the digester or the fill level inside the digester has to be lowered • Maintenance hatches have to be integrated into the digester • Comply with applicable health and safety regulations for working inside the digester

Figure 3.31: Propeller SMA (left), guide-tube system (centre), large-blade rotor SMA (right) [Agrartechnik Lothar Becker (left, centre), KSB AG]

In *upright* stirred-tank digesters the horizontal agitator shaft is carried on a steel supporting structure. It is not possible to change the orientation of the shaft. Good intermixing inside the digester is achieved with the aid of a corresponding, shear-based agitator. An example is shown in Figure 3.34. The properties are listed in Table 3.25.

Pneumatic mixing

Pneumatic mixing of substrate is offered by a few manufacturers, but it is not of major significance in agricultural biogas plants.

Pneumatic mixing involves blowing biogas into the digester through nozzles at floor level. The gas bubbling up through the substrate creates vertical movement, mixing the substrate.

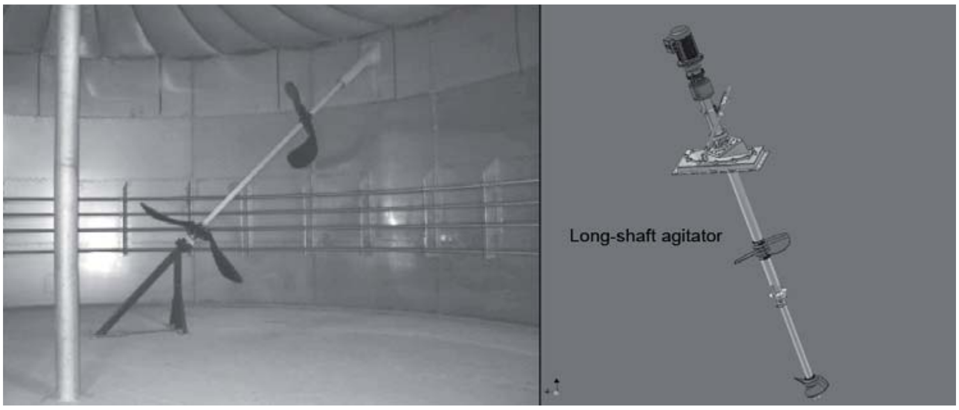

Figure 3.32: Long-shaft agitators with two stirring blades with and without shaft-end bearer on the bottom of the digester [WELtec BioPower GmbH; graphic: Armatec FTS-Armaturen GmbH & Co. KG]

Table 3.24: Characteristic values and process parameters of axial agitators for biogas plants

Characteristic values	• Low-speed, continuous-operation agitators • Available power range: up to 25 kW • Speed depends on the substrate; has to be determined during the plant shakedown phase • Material: corrosion-resistant, usually special steel • Power draw: e.g. 5.5 kW for 3,000 m^3, usually higher
Suitability	• All substrates in wet digestion, only in large, upright digesters
Advantages	+ Good intermixing in the digester can be achieved + Virtually no moving parts inside the digester + Drive is maintenance-free outside the digester + Thin layers of scum can be drawn down into the substrate + Continuous settlement and scumming processes are largely prevented
Disadvantages	- Siting is stationary, so there is a risk of incomplete mixing - Consequently, possibility of scum and settlement layers forming in parts of the digester, particularly in the areas close to the edge - Shaft bearing is subject to severe strain, so maintenance outlay can be considerable
Special considerations	• Glands carrying the agitator shaft must be gastight • Variable-speed control with frequency converters is possible
Designs	• Out-of-tank electric motors with gearing, in-tank agitator shaft with one or more propellers or rotors, as bottom-standing or overhead agitators • Propeller can be installed in a guide duct to encourage flow formation • Off-centre siting is possible
Maintenance	• Motor maintenance is straightforward on account of siting outside the digester; no need to interrupt the process • Repairs to rotors and shaft difficult, because they have to be taken out of the digester or the fill level of the substrate in the digester has to be lowered • Maintenance hatches have to be integrated into the digester • Comply with applicable health and safety regulations for working inside the digester

The advantage of these systems is that the mechanical components necessary for mixing (pumps and compressors) are sited outside the digester and are therefore subject to no more than low rates of wear. These techniques are not suitable for breaking up scum, so they can be used only for runny substrates with no more than slight tendency to scumming. Characteristic values of systems for pneumatic mixing are listed in Table 3.26.

Hydraulic mixing

When it is mixed hydraulically, substrate is forced into the digester by pumps and horizontally or horizontally and vertically swivelling agitator nozzles. The substrate has to be extracted and returned in such a way that the contents of the digester are stirred as thoroughly as possible.

Hydraulically mixed systems also have the advantage of siting the mechanical components necessary

Table 3.25: Characteristic values and process parameters of paddle/paddle-wheel agitators in upright and horizontal digesters

Characteristic values	• Low-speed, intermittent-operation agitators • Power draw: depends heavily on site and on substrate; significantly higher in dry digestion on account of the high resistance of the substrate • Speed depends on the substrate; has to be determined during the plant shakedown phase • Material: corrosion-resistant, usually coated steel but special steel also possible
Suitability	• All substrates in wet digestion (especially for substrates rich in dry matter)
Advantages	+ Good intermixing in the digester can be achieved + Drive is maintenance-free outside the digester; adapter for PTO drive also possible + Settlement and scumming processes are prevented
Disadvantages	- The digester has to be emptied to permit servicing of the paddles - In the event of a breakdown in dry digestion, the entire digester has to be emptied manually (stirring (secondary agitator) and pumping out might be possible) - Siting is stationary, so risk of incomplete mixing; secondary drives are necessary to ensure flow in the digester (generally compacting screws in horizontal digesters, shear-based agitators in upright stirred-tank digesters)
Special considerations	• Glands carrying the agitator shaft must be gastight • Variable-speed control with frequency converters is possible
Designs	• Out-of-tank electric motors with gearing, in-tank agitator shaft with two or more paddles, to some extent possibility of installing heat-exchanger tubing as secondary mixers on the shaft or as a unit with the paddles (in horizontal digesters)
Maintenance	• Motor maintenance is straightforward on account of siting outside the digester; no need to interrupt the process • Repair of paddles and shaft difficult, because the digester has to be emptied • Maintenance hatches have to be integrated into the digester • Comply with applicable health and safety regulations for working inside the digester

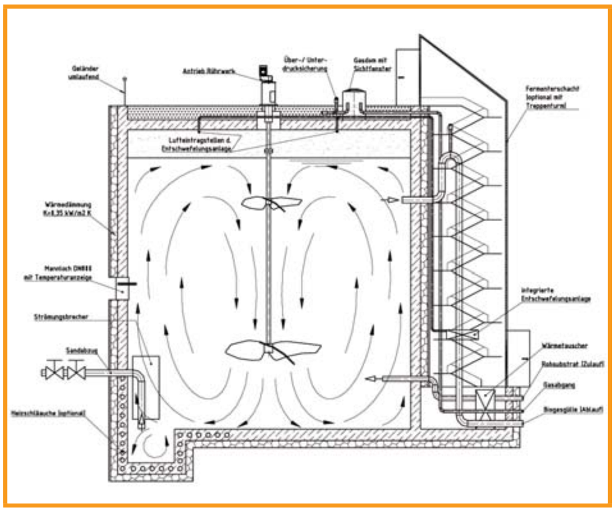

Figure 3.33: Axial agitator [ENTEC Environmental Technology Umwelttechnik GmbH]

Figure 3.34: Paddle agitator [PlanET GmbH]

for mixing outside the digester. They are consequently subject to no more than low rates of wear and are easily serviced. Hydraulic mixing is only conditionally suitable for breaking up scum, so it can be used only for runny substrates with no more than slight tendency to scumming. As regards gauging pump technology, the information in Section 3.2.1.4 is also of note. Table 3.27 provides an overview of the characteristic values and process parameters of hydraulic mixing.

Removal of digested substrate

Digesters of the stirred-tank reactor type usually have an overflow working on the siphon principle to prevent the escape of gas. The digested substrate can also be pumped off. It is advisable to stir the material

Table 3.26: Characteristic values and process parameters of pneumatic mixing in digesters

Characteristic values	• Power draw: e.g. 15 kW compressor for 1,400 m^3 digester, quasi-continuous operation • Available power range: 0.5 kW and upward, all ranges for biogas plants possible
Suitability	• Very runny substrates with little tendency to form floating scum
Advantages	+ Good intermixing in the digester can be achieved + Gas compressors are outside the digester, so servicing is straightforward + Settlement layers are prevented from forming
Disadvantages	- The digester has to be emptied to permit servicing of the biogas injector system
Special considerations	• Compressor technology must be compatible with the composition of the biogas
Designs	• Uniform nozzle distribution over the entire bottom of the digester or mammoth-pump principle with biogas forced into a vertical duct • Used in combination with hydraulic or mechanical mixing
Maintenance	• Gas-compressor maintenance is straightforward on account of siting outside the digester; no need to interrupt the process • Repair of biogas injection equipment difficult, because the digester has to be emptied • Comply with applicable health and safety regulations for working inside the digester

Table 3.27: Characteristic values and process parameters of hydraulic mixing in digesters

Characteristic values	• Use of high-capacity pumps • Power data: correspond to the normal pump data as set out in Section 3.2.1.4 • Material: same as pumps
Suitability	• All easily pumpable substrates in wet digestion
Advantages	+ Good mixing achievable inside the digester with adjustable submersible rotary pumps or in ducts; also capable of breaking up scum and settlement layers
Disadvantages	- Settlement layers and scum can form if external pumps are used without provision for control of the flow direction inside the digester - Settlement layers and scum cannot be removed if external pumps are used without provision for control of the flow direction inside the digester
Special considerations	• See Section 3.2.1.4 for details of special considerations concerning this equipment
Designs	• Submersible rotary pump or dry-sited rotary pump, eccentric single-rotor screw pump or rotary displacement pump, see Section 3.2.1.4 • Externally sited pumps can have entry ports fitted with movable deflectors or nozzles; changeover between various entry ports is possible
Maintenance	• The equipment-specific maintenance considerations are the same as those stated in Section 3.2.1.4

before removing it from a digestate tank. This achieves a uniform consistency and quality of the biofertiliser for the end user, for example agriculture. Agitators with PTO drive have proved acceptable for applications of this nature; the economic balance benefits from the fact that equipment of this type has no permanent need for a motor. Instead it can be coupled up to a tractor engine to stir up the digestate when it is ready to be pumped out.

In horizontal digesters, the plug flow produced by the infeed of fresh substrate discharges the digested material through an overflow or a discharge pipe sited below the surface level of the substrate.

3.2.2.4 Other ancillary systems

Many biogas plants have systems that are not absolutely necessary for normal operating routines, but which can be useful – mostly depending on the substrate – on a case-to-case basis. Means of preventing the formation of floating scum and settlement layers are discussed below. The post-biogassing process step of solid/liquid separation is also described.

Foam trap and foaming control

Foaming can occur in wet-digestion digesters, depending on the substrate used or, more accurately, on the composition of the substrate. This foam can clog the gas pipes for biogas extraction, which is the reason why the gas discharge should always be sited as high as possible inside the digester. Foam traps prevent foam

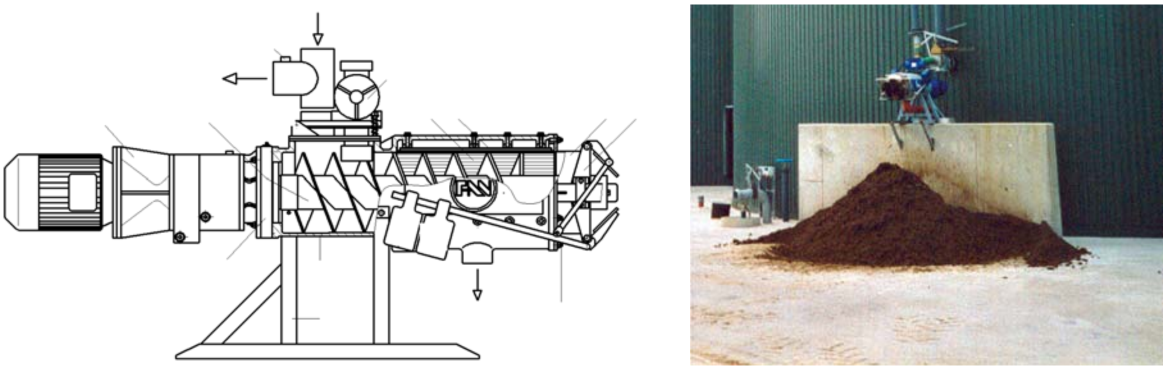

Figure 3.35: Screw separator [FAN Separator GmbH (left); PlanET Biogastechnik GmbH]

from making its way into the substrate pipes to the downline digesters or storage ponds. See Figure 3.36 for an impression of the arrangement of the inlets and outlets.

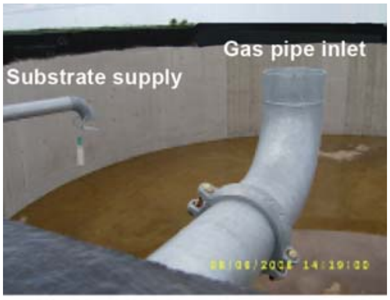

Figure 3.36: Provisions to prevent disruption of gas extraction; gas pipe inlet with intake opening upward (substrate feed inlet is to the left) [DBFZ]

A foam sensor designed to trigger an alert if foaming becomes excessive can also be installed in the digester's gas space. If foaming is too severe, one possibility is to spray foam inhibitors into the digester, but this entails installing the necessary equipment in the digester. This can consist of a sprayer system. Another matter that has to be taken into consideration, however, is that the fine holes in spray tubes can be attacked in the corrosive gas atmosphere. This can be prevented by operation of the sprayer system at regular intervals, even if foaming does not occur. Foam inhibitors suitable for this application include oils – preferably vegetable oil. Water sprinkled over the liquid phase can also be of assistance as an emergency measure.

Removing sediment from the digester

Sediments and settlement layers form when dense materials such as sand settle out of the substrate during wet digestion. To separate the dense materials, pre-digester pits are equipped with heavy-material separators, but sand can be compounded very firmly with the organic matter (this is often the case with manure from poultry farms, for example), with the result that very frequently, only stones and other coarse heavy materials can be removed in pre-digester pits. A large proportion of the sand is released only later, in the course of biodegradation in the digester.

Certain substrates such as pig manure and poultry droppings can assist the formation of these layers. Settlement layers can become very thick over the course of time, effectively reducing the digester's usable capacity. Digesters have been found to be half-filled with sand. Settlement layers also have a propensity to harden, and can then be removed only with spades or mechanical diggers. Bottom scrapers or a bottom drain make it possible to discharge settlement layers from the digester. If settlement layer formation is severe, however, there is no guarantee that the sediment discharge system will remain fully functional, so it might be necessary to open the digester to permit removal of settlement layers by manual means or by suitable mechanical equipment. Possible means of removing or discharging sediment are listed in Table 3.28. In very tall digesters over 10 metres in height, static pressure can be sufficient to discharge sand, lime and sludge.

Solid/liquid separation

As the proportion of stackable substrates in biogas recovery increases, more consideration has to be given to the source of the liquid for wetting down to mash and the capacity of the digestate storage tank. A farm's storage tank is frequently sized to accommodate liquid manure arisings, but it cannot also accommodate additional post-digestion substrate. Under circumstances like this it can be economically and technologically viable to resort to solid/liquid separa-

Table 3.28: Sediment discharge and removal systems

Characteristic values	• Characteristics of the equipment used in sediment discharge and removal systems correspond to those of the individual items of equipment described above
Suitability	• Bottom scrapers only in upright digesters with circular, smooth bottom • Discharge screw conveyors in horizontal and upright digesters • Conical bottoms in upright digesters
Special considerations	• Characteristics of the equipment used in sediment discharge and removal systems correspond to those of the individual items of equipment described above • Discharge screw conveyors must have either liquid-tight glands through the side wall of the digester or gastight glands through the cover above the side wall • Discharge can be associated with a severe odour nuisance • A pump sump or the like has to be integrated into the digester for discharge screw conveyors
Designs	• Bottom scrapers with out-of-tank drive to carry the sediment out of the digester • Discharge screw conveyors on the bottom of the digester • Conical digester bottom with discharge pump and settlement layer stirring or flushing system
Maintenance	• Maintenance of permanently installed systems requires emptying the digester, so out-of-tank drives or removal equipment have advantages • Comply with applicable health and safety regulations for working inside the digester

tion. The liquid pressed out of the mass can be used as make-up liquid for mashing or as liquid manure, and the solids fraction takes up less storage space or can be composted.

Belt-type filter presses, centrifuges and screw or worm separators can be used for solid/liquid separation. Worm separators are the most common, so their characteristic values are listed in Table 3.29. Figure 3.35 shows a sectional view through a worm separator and an example of a separator in operation

3.2.2.5 Heating and thermal insulation

Thermal insulation of the digester

Digesters require additional thermal insulation in order to reduce heat loss. Commercially available materials can be used for thermal insulation, although in terms of their properties the materials used should be selected to suit the location (close proximity to the ground, etc.) (see Table 3.30). Table 3.31 contains an overview of the parameters and some examples of insulating materials. Trapezoidal metal sheeting or wood panelling is used to protect the insulating material against the effects of the weather.

Digester heating

The temperature inside the digester has to be uniform, in order to ensure an optimum digestion process. In this respect it is not so much maintaining the specified temperature to within one tenth of a degree that is important as keeping temperature fluctuations within tight limits. This applies to temperature fluctuations over time and also to temperature imbalance in different parts of the digester [3-3]. Severe fluctuations and excursions above or below certain temperature levels can impede the digestion process or even bring

Table 3.29: Worm separators

Suitability	• For pumpable substrates that can be transported by worm-type conveyors • For substrates from 10% dry matter to approx. 20% dry matter (the product can contain up to 30% dry matter in the solid phase)
Special considerations	• Add-on options such as oscillators can make dewatering more effective • Fully automatic operation is possible
Designs	• Freestanding unit • Installation upstream of the biogas reactor in plants with very short dwell times is possible; this can produce savings on agitator design and avoidance of breakdowns caused by solids, and also less formation of settlement layers and surface scum • Installation downstream from the reactor to return make-up liquid for wetting down to mash and save on agitators in the digestate storage tank
Maintenance	• Readily accessible unit, maintenance is possible without interrupting the overall process

Table 3.30: Characteristic values of insulating materials [3-12], [3-13]

Characteristic values	• Material in the digester or below grade level: closed-pore substances, such as PU rigid foam and foamed glass, that prevent moisture penetration • Material above grade level: rock wool, mineral-fibre matting, rigid-foam matting, extrusion foam, Styrodur, synthetic foams, polystyrene • Material thickness: 5-10 cm are used, but insulating effect is low at less than 6 cm; empirical values are based more on experience than on calculations; there are reports of thicknesses up to 20 cm in the literature • Heat transfer coefficients are in the range from 0.03 - 0.05 W/($m^2 \cdot K$) • Loadability of the insulating material underfoot must be suitable for the complete load of the fully charged digester
Designs	• Thermal insulation can be internal or external; there is no evidence to indicate that either is better in all circumstances.
Special considerations	• All insulating materials should be rodent-proof

Table 3.31: Characteristic values of insulating materials – examples

Insulating material	Thermal conductivity [W/m · K]	Type of application
Mineral-fibre insulating materials (approx. 20-40 kg/m³)	0.030-0.040	WV, WL, W, WD
Perlite insulating sheets (150-210 kg/m³)	0.045-0.055	W, WD, WS
Polystyrene particle foam EPS (15 kg/m³ < bulk density)	0.030-0.040	W
Polystyrene particle foam EPS (20 kg/m³ < bulk density)	0.020-0.040	W, WD
Polystyrene extrusion foam EPS (25 kg/m³ < bulk density)	0.030-0.040	WD, W
Polyurethane rigid foam EPS (30 kg/m³ < bulk density)	0.020-0.035	WD, W, WS
Foamed glass	0.040-0.060	W, WD, WDS, WDH

Types of application: WV with tear-off and shear loading; WL, W without compressive loading; WD with compressive loading; WS insulating materials for special areas of application; WDH increased loadability under compression-spreading flooring; WDS increased loadability for special areas of application

it to a complete standstill under worst-case conditions. The causes of temperature fluctuations are many and varied:
- infeed of fresh substrate;
- temperature stratification or temperature zone formation on account of insufficient thermal insulation, ineffective or incorrectly planned heating, insufficient mixing;
- positioning of the heating elements;
- extreme ambient temperatures in summer and winter;
- equipment failures.

The substrate has to be heated in order to achieve the necessary process temperatures and to compensate for heat losses; this can be done by heat exchangers or heaters either installed externally or integrated into the digester.

Integrated heaters heat the substrate inside the digester. Table 3.32 provides an overview of the technologies involved; Figure 3.37 shows examples.

External heat exchangers heat the substrate before it is fed into the digester, so the substrate is preheated before entering the digester. This helps avoid temperature fluctuations associated with substrate infeed. When external heat exchangers are used, either substrate recirculation through the heat exchanger must be continuous or an extra internal heater inside the digester is indispensable, in order to maintain a constant temperature inside the digester. The properties of external heat exchangers are listed in Table 3.33.

3.2.3 Storing digested substrate

3.2.3.1 Liquid digestate

In principle, storage can be in ponds or in cylindrical or box-section tanks (above-grade and sub-grade tanks). Upright tanks made of concrete and special steel/steel enamel are the most common. Their basic structure is comparable to that of upright stirred-tank reactors (see Section 3.2.2.1, Digester designs). These tanks can be equipped with agitators so that the liquid digestate can be homogenised prior to being discharged from the holding tank. The agitators used can be of the permanently installed (e.g. submersible-mo-

Table 3.32: Characteristic values and process parameters of integrated heating systems [3-1], [3-12]

Characteristic values	• Material: when installed in the digester space or as agitator special-steel piping, PVC or PEOC (the thermal conductivity of plastics is low, so the spacing has to be tight); ordinary underfloor heating pipes if laid in concrete
Suitability	• Wall heaters: all types of concrete digester • In-floor heating: all upright digesters • Interior heating: all types of digester, but more common in upright digesters • Heaters connected to agitators: all types of digester, but more common in horizontal digesters
Advantages	+ Heating systems that are laid horizontally in the digester and those connected to agitators transfer heat effectively + In-floor heaters and wall heaters do not cause deposits + Heaters integrated into agitators come into contact with much more material for heating
Disadvantages	- Effect of in-floor heating can be severely reduced by the formation of settlement layers - Heaters inside the digester space can cause deposits, so they should be kept a certain distance away from the walls.
Special considerations	• Provision must be made for venting heating pipes; for this purpose the direction of flow is bottom-up • Heating elements laid in concrete cause thermal stresses • Two or more heating circuits needed, depending on the size of the digester • The heating must not obstruct other items of equipment (e.g. scrapers) • Heaters set in the wall or in the bottom of the digester are not suitable for thermophilic operation
Designs	• In-floor heating systems • In-wall heating systems (can also be in the outer jacket in the case of steel digesters) • Heaters mounted on spacers off the wall • Heaters integrated into or combined with the agitators
Maintenance	• Heaters have to be cleaned regularly in order to ensure that heat transfer remains effective • Access to heaters integrated into the digester or the structure is very difficult, if not impossible • Comply with applicable health and safety regulations for working inside the digester

Figure 3.37: Special-steel heating pipes laid in the digester (inside) (left); installation of heating tubes in the digester wall (right) [Biogas Nord GmbH; PlanET Biogastechnik GmbH (right)]

tor agitator) or PTO-driven types of side-driven, shaft-driven or tractor-tow-driven design. The storage tanks can also be covered (gastight or not gastight). Both arrangements have the advantage of reducing odour nuisance and lowering nutrient losses during storage. Gastight covers such as plastic sheeting for example (see Section 3.2.4.1, Integrated storage spaces) also afford the opportunity of utilising the residual-gas potential of the digestate and can be used as additional gas storage spaces. The necessity for gastight covers is open to discussion in relation to the substrates used, the dwell time and various aspects of process control, but in many instances provision of a cover of this nature is a condition without which planning permission for a new plant will not be forthcoming. In the latest edition of the Renewable Energy Sources Act as issued and amended on 1 January 2009, even plants approved in accordance with the Bundes-Immissionsschutzgesetz (Federal German Pollution Control Act) need gastight covers for the digestate storage tanks if they are to be eligible for the NawaRo bonus for renewable resources (see Chapter 7).

Table 3.33: Characteristic values and process parameters of external heat exchangers [3-3], [3-12]

Characteristic values	• Material: generally special steel • Throughput ratings are oriented toward plant capacity and process temperature • Pipe diameters correspond to the usual diameters for substrate pipes in biogas plants
Suitability	• All types of digester, frequently used in reactors operating on the plug-flow principle
Advantages	+ Very good heat transfer can be ensured + Fresh material does not produce temperature shock inside the digester + The heating comes into contact with the entire volume of material + External heat exchangers are easily cleaned and serviced + Good temperature controllability
Disadvantages	- Under certain circumstances it might be necessary to provide additional digester heating - The external heat exchanger is an extra item of equipment, with the associated additional costs
Special considerations	• Provision must be made for venting heat exchangers; for this purpose the direction of flow is bottom-up • Eminently suitable for thermophilic process control
Designs	• Spiral-tube or jacketed-tube heat exchangers
Maintenance	• Very good accessibility for maintenance and cleaning

Table 3.34: Characteristic values and process parameters of plastic-sheet covers, including some data from [3-3]

Characteristic values	• Gas storage capacities up to 4,000 m^3 available • Gauge pressures: 5-100 mbar • Permeability of plastic sheeting: expect biogas losses of 1-5‰ per day • Materials: butyl rubber, polyethylene-polypropylene mixture, EPDM rubber
Suitability	• For all biogas plants with upright digesters and secondary digesters with diameters as large as possible
Advantages	+ No additional building necessary + No additional space necessary
Disadvantages	- On account of the severe gas mixing taking place in the large gas space, the true methane concentration in the digester's gas space cannot be measured and consequently cannot reflect the activity of the microorganisms - Without an extra roof structure the thermal insulation vis-à-vis the gas space is only slight - Easily caught by wind if there is no additional roof structure
Special considerations	• Thermal insulation by double thickness of plastic sheeting with air blown into the space between the two (floating roof) • Agitators cannot be installed on top of the digester
Designs	• Plastic sheeting as roof over the digester • Plastic sheeting underneath a floating roof • Plastic sheeting underneath a solid roof of a raised digester • Secured or unsecured cushion made of plastic sheeting • Encased plastic-sheeting cushion in an extra building or tank • Plastic-sheeting cushion on a suspended roof above the digester • Plastic sheeting sack, suspended inside a building (e.g. unused barn) • Plastic-sheeting storage space underneath floating roof
Maintenance	• Maintenance-free to a very large extent

Ponds are generally rectangular, sub-grade structures with plastic-sheet liners. Most of these ponds are open to the air; there are no more than a few ponds that have plastic sheeting covers to reduce emissions.

The size of the digestate storage tank is defined primarily by the optimum time for spreading digestate on the fields requiring fertilisation. Reference is made in this context to the 'Düngeverordung', the Fertiliser Application Ordinance, and to Chapter 10, Field spreading of digestate. Digestate storage facilities are generally designed for a capacity of at least 180 days.

3.2.3.2 Solids

Solid residues are produced in dry digestion and they also arise as separated fractions of the spent digestate from wet-digestion processes. Depending on intended use, they are stored in surfaced outdoor bays or inside structures, or in open and sometimes mobile vessels and containers. The most common form of storage is in piles on liquid-nonpermeable concrete or asphalt stands, in much the same way as piles of solid manure. Empty mobile silos are also pressed into service as storage facilities on occasion. Dripping liquids, the water pressed out of the mass and rainwater have to be caught and returned to the biogas plant. Precipitation can be kept off the solid residues by plastic sheeting or permanent roofing structures.

Steel drums are used primarily when the solid fraction is pressed out of liquid digestate. They can be placed underneath the separator (cf. Figure 3.36) and removed when full. In this case too, the drums should be covered to keep precipitation off their contents. Alternatively, solid/liquid separation and the storage of the solid fraction can be sited indoors. If the equipment is indoors the spent air can be extracted if necessary and ducted to a cleaning system (e.g. scrubber and/or biofilter).

3.2.4 Storing the recovered biogas

Biogas arisings fluctuate in quantity and to some extent output peaks are encountered. Consequently, and because usable volume should be constant to a very large extent, the biogas has to be buffered in suitable storage tanks. The gas storage tanks must be gastight, pressure-tight and resistant to the medium, to ultraviolet light, temperature and weathering. The gas storage tanks have to be tested before being commissioned to ensure that they are gastight. For safety reasons gas storage tanks have to be fitted with overpressure and negative-pressure relief valves in order to avoid impermissibly severe changes in the pressure inside the vessel. Other codes that set out safety requirements and regulations for gas storage tanks include the 'Sicherheitsregeln für landwirtschaftliche Biogasanlagen' (Safety Rules for Biogas Systems) [3-18]. The design of the tanks must be such that they can buffer approximately one quarter of daily biogas yield; a capacity of one or two days' production is frequently recommended. Distinctions can be drawn between low-pressure, medium-pressure and high-pressure tanks.

Low-pressure tanks are the most common, operating at 0.5 to 30 mbar gauge pressure. Low-pressure tanks are made of plastic sheeting that must be in compliance with the applicable safety requirements. Storage tanks made of plastic sheeting are installed as gas hoods on top of digesters (integrated storage tanks) or as external storage facilities. See Sections 3.2.4.1 and 3.2.4.2 for details.

Medium-pressure and high-pressure storage tanks store biogas at operating pressures between 5 and 250 bar in pressurised steel containers and bottles [3-1]. They are expensive and operating overheads are high. Energy input for pressurised tanks up to 10 bar can be up to 0.22 kWh/m^3 and the corresponding figure for high-pressure tanks with 200-300 bar is in the region of 0.31 kWh/m^3 [3-3]. This is the reason why they are virtually never used in agricultural biogas plants.

3.2.4.1 Integrated storage tanks

Hoods made of plastic sheeting are used to store the gas in the digester itself or in the secondary digester or the digestate storage tank. The plastic sheeting forms a gastight seal round the top of the tank. A supporting structure is set up in the tank; when there is no gas in storage the plastic sheeting is draped on and supported by this structure. The plastic sheeting balloons up as the gas storage space fills. Characteristic values are listed in Table 3.34, and Figure 3.38 shows examples.

Storage tanks of the floating-roof type are common. They generally have a second plastic sheet spread on top of the gas-retaining sheet for added protection against the weather. A blower blows air into the space between the two thicknesses of sheeting. This keeps the top, outer sheeting taut at all times, whereas the inner sheeting can adapt to the volume of biogas stored. This system is capable of maintaining a reasonably constant gas pressure.

3.2.4.2 External storage tanks

Plastic-sheeting cushions can be used as external low-pressure storage tanks. The cushions are housed inside suitable buildings to protect them from the weather, or are protected by a second layer of sheeting (Figure 3.39). Figure 3.40 shows an example of external gas storage tanks of this nature. The specifications of external gas storage tanks are listed in Table 3.35.

3.2.4.3 Emergency flare

In case the storage tanks are unable to take more biogas and/or the gas cannot be used on account of maintenance work or extremely poor quality, the excess has to be disposed of in a safe manner. In Germany,

Table 3.35: Characteristic values and process parameters of external biogas storage tanks, including some data from [3-3]

Characteristic values	• Gas storage capacities up to 2,000 m³ are available (tanks with larger capacities can be built to customer specification) • Gauge pressures: 0.5-30 mbar • Permeability of plastic sheeting: expect biogas losses of 1-5‰ per day • Materials: PVC (not very durable), butyl rubber, polyethylene-polypropylene compound
Suitability	• For all biogas plants
Advantages	+ The methane concentration of the biogas currently being generated can be metered inside the digester's gas space (mixing is not severe in this space on account of the low volume of gas) and mirrors the activity of the microorganisms
Disadvantages	- Extra space possibly needed - Extra building possibly needed
Special considerations	• Applying weights is a simple way of increasing pressure to expel gas to the CHP unit • If installed inside buildings, a very good supply of air to the interior of the building is essential in order to prevent the formation of explosive mixtures • Engine power output of the CHP unit can be adjusted as a function of fill level
Designs	• Secured or unsecured cushion made of plastic sheeting • Encased plastic-sheeting cushion in an extra building or tank • Plastic-sheeting cushion on a suspended roof above the digester • Plastic sheeting sack, suspended inside a building (e.g. unused barn) • Plastic-sheeting storage space underneath floating roof
Maintenance	• Maintenance-free to a very large extent

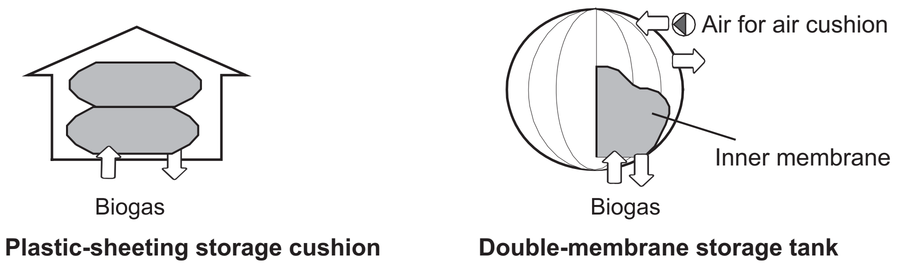

Figure 3.38: Plastic-sheeting storage tank [ATB Potsdam]

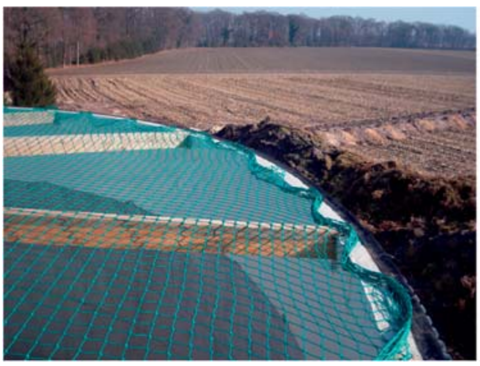

Figure 3.39: Supporting structure of a floating roof (left); biogas plant with floating-roof tanks [MT-Energie GmbH]

Table 3.36: Characteristic values and process parameters of emergency flares

Characteristic values	• Volume flow rates up to 3,000 m^3/h possible • Ignition temperature 800–1,200 °C • Material: steel or special steel
Suitability	• For all biogas plants
Special considerations	• Open or covered combustion possible • If combustion chamber is insulated, compliance with TA Luft (Technical Instructions on Air Quality Control) is possible, although this is not mandatory for emergency flares • Available with natural draft or blower • It is important to comply with safety instructions, particularly in relation to clearance from the nearest buildings • The pressure of the biogas has to be increased upstream of the burner jet
Designs	• Separate unit on its own small concrete foundation, for manual operation or automated
Maintenance	• Maintenance-free to a very large extent

Figure 3.40: Example of a freestanding plastic-sheeting storage tank with two thicknesses of plastic sheeting [Schüsseler, FNR]

Figure 3.41: Emergency flare of a biogas plant [Haase Umwelttechnik AG]

the regulations relating to the operating permit vary from state to state, but installation of an alternative to the CHP unit as ultimate sink is required if the gas flow rate is 20 m^3/h or higher. This can take the form of a second cogeneration unit (for example two small CHP units instead of one large one). A margin of safety can be established by installing an emergency flare, as a means of ensuring that the gas can be disposed of in an adequate way. In most cases the authorities stipulate that a provision of this nature be made. Characteristic values of emergency flares used in the biogas industry are shown in Table 3.36. An example is shown in Figure 3.41.

3.3 Relevant engineering codes

Over and above the laws on plant safety, occupational health and safety and environmental protection, there are a number of codes dealing with technical requirements applicable to biogas plants. Some of the most important are listed below by way of example:

VDI Guideline 3475 Blatt 4 (draft) Emission control – Agricultural biogas facilities – Digestion of energy crops and manure

VDI Guideline 4631 (draft) Quality criteria for biogas plants
DIN 11622-2 Silage and liquid manure containers
DIN 1045 Concrete, reinforced concrete and pre-stressed concrete structures
DIN EN 14015 Specification for the design and manufacture of site-built, vertical, cylindrical, flat-bottomed, above-ground welded steel tanks for the storage of liquids at ambient temperature and above
DIN 18800 Steel structures
DIN 4102 Fire behaviour of building materials and building components
DIN 0100 Part 705 Low-voltage electrical installations
VDE 0165 Part 1/ EN 60 079-14
Explosive atmospheres, electrical installations design, selection and erection – Part 14: Electrical installations in explosive atmospheres (except mining)
VDE 0170/0171 Electrical apparatus for potentially explosive atmospheres
VDE 0185-305-1 Protection against lightning
G 600 Technical rules for gas installations DVGW-TRGI 2008
G 262 Utilisation of gases from renewable sources in the public gas supply
G 469 Pressure-testing methods for gas-supply pipes and facilities
VP 265 ff Plants for the treatment of biogas and injection into natural gas networks

Section 5.4 'Operational reliability' contains detailed information on other safety-related requirements for the operation of biogas plants. In particular, the section deals with safety regulations in relation to the risks of poisoning and asphyxiation, fire and explosion.

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Source: FNR

4 Description of selected substrates

This chapter examines selected substrates in closer detail. It looks at the origin of the substrates and at their most important properties, such as dry matter (DM; also referred to as total solids – TS), volatile solids (VS; also referred to as organic dry matter – ODM), nutrients (N, P, K) and any organic contaminants that may be present. There is also a discussion of the expected gas yields and gas quality, as well as the methods of handling the substrates.

As it is impossible to describe the entire spectrum of potentially available substrates, this chapter does not claim to be exhaustive. Since the substrates described here are also subject to annual fluctuations in quality, the material data and gas yields quoted in this chapter should not be considered as absolute values. Instead, both a range and an average value of each parameter are given.

The figures for biogas yields and methane yields are stated in units of normal cubic metres (Nm^3). As the volume of gas is dependent on temperature and atmospheric pressure (ideal gas law), normalisation of the volume enables comparisons to be made between different operating conditions. The normalised gas volume is based on a temperature of 0 °C and an atmospheric pressure of 1013 mbar. In addition, it is possible in this way to assign a precise calorific value to the methane component of the biogas; for methane this is 9.97 kWh/Nm^3. The calorific value can in turn be used to deduce figures for energy production, which may be necessary for various comparative calculations within the plant.

4.1 Substrates from agriculture

4.1.1 Manure

Taking the statistics for the numbers of livestock in Germany as a basis, it is plain that cattle and pig farming in particular offer tremendous potential for energy recovery in biogas plants. The increasing size of farms in animal husbandry and stricter environmental standards for the further exploitation of excrement are two of the main reasons why alternative means of utilising and treating the accruing slurry or solid manure need to be found. Also with climate change mitigation in mind, there is a need to utilise manure for energy recovery in order to achieve a significant reduction in stock emissions. The most important material data for manure can be taken from Table 4.1.

The biogas yield from cattle slurry, at 20-30 Nm^3 per t of substrate, is slightly below that from pig slurry (cf. Table 4.2). Furthermore, the gas from cattle slurry has a considerably lower average methane content compared with that from pig slurry, and thus also a lower methane yield. This is attributable to the different compositions of these types of manure. Cattle slurry contains largely carbohydrates, while pig slurry consists for the most part of proteins, which give rise to the higher methane content [4-3]. The biogas yield is primarily determined by the concentrations of volatile solids (organic dry matter). If liquid manure is diluted, as often happens in practice (for example as a result of the cleaning of cowsheds or milking parlours), the actual material data and biogas yields may well differ significantly from those shown in Table 4.2.

Both cattle slurry and pig slurry can be used without difficulty in biogas plants thanks to their pumpability and simplicity of storage in slurry tanks. Furthermore, because of their relatively low total solids content, they can be easily combined with other sub-

Table 4.1: Nutrient concentrations of various types of farm manure (after [4-1], modified)

Substrate		DM [%]	VS [% DM]	N	NH_4	P_2O_5	K_2O
				[% DM]			
Cattle slurry	Δ	6-11	75-82	2.6-6.7	1-4	0.5-3.3	5.5-10
	∅	10	80	3.5	n.s.	1.7	6.3
Pig slurry	Δ	4-7	75-86	6-18	3-17	2-10	3-7.5
	∅	6	80	3.6	n.s.	2.5	2.4
Cattle dung	Δ	20-25	68-76	1.1-3.4	0.22-2	1-1.5	2-5
	∅	25	80	4.0	n.s.	3.2	8.8
Poultry manure	∅	40	75	18.4	n.s.	14.3	13.5

Δ: range of measured values; ∅: average

Table 4.2: Gas yield and methane yield from various types of farm manure (after [4-2], modified)

Substrate		Biogas yield [Nm^3/t substrate]	Methane yield [Nm^3/t substrate]	Specific methane yield on VS basis [Nm^3/t VS]
Cattle slurry	Δ	20-30	11-19	110-275
	∅	25	14	210
Pig slurry	Δ	20-35	12-21	180-360
	∅	28	17	250
Cattle dung	Δ	60-120	33-36	130-330
	∅	80	44	250
Poultry manure	Δ	130-270	70-140	200-360
	∅	140	90	280

Δ: range of measured values; ∅: average

strates (co-substrates). In contrast, loading solid manure into the reactor involves much greater technical complexity. The viscous consistency of solid manure means that it cannot be processed by every solids charging technology available on the market.

4.1.2 Energy crops

Since the Renewable Energy Sources Act (EEG) was first amended in 2004, particular importance has been attached to energy crops (renewable raw materials) in connection with the generation of electricity from biogas. Energy crops are used in most of the new biogas plants that have been built since that time. A selection of the energy crops in most common use is described in more detail in the following, with additional information on the crops' material properties and biogas yields.

When a decision is being taken as to what crops to grow, the focus should not be placed solely on the highest yield obtainable from a single crop, but instead, if possible, an integrated view should be taken of the entire crop rotation. By including labour efficiency considerations, for example, and sustainability criteria relating to alternative cultivation methods, a holistic approach can be taken to optimising the growing of energy crops.

4.1.2.1 Maize

Maize (corn) is the most commonly used substrate in agricultural biogas plants in Germany [4-4]. It is particularly well suited because of its high energy yields per hectare and the ease with which it can be used for digestion in biogas plants. Crop yields are heavily dependent on local and environmental conditions, and may vary from 35 t fresh mass (FM) on sandy soils to over 65 t FM/ha at high-yielding locations. On average, the yield is roughly 45 t FM/ha. Maize is a relatively undemanding crop, and is therefore suitable for almost any location throughout Germany.

When harvested, the entire maize plant is chopped and then stored in horizontal silos. The dry matter (total solids) content should not be below 28% DM and not above 36% DM. If the dry matter content is below 28% DM, it must be expected that there will be a considerable escape of seepage water, associated with significant energy losses. If the dry matter content is above 36% DM, the silage has a high lignin content and is thus less easily degradable. Furthermore, the silage can no longer be optimally compacted, which in turn has a detrimental effect on ensiling quality and hence storage stability. After being loaded into the silo the chopped plant parts are compacted (for example by wheel loader or farm tractor) and sealed with an air-tight plastic sheet. After an ensilage phase of roughly 12 weeks, the silage can be used in the biogas plant. The material data and average biogas yields are given at the end of this chapter.

Alongside use of the whole plant as silage maize, use of just the maize ear (corn cob) has gained a certain significance in real-world applications. Common variants are ground ear maize (GEM), corn cob mix (CCM) and grain maize, obtained by harvesting at different times and using different techniques. GEM and CCM are normally ensiled after harvesting. Grain maize can either be ensiled when wet, ground and ensiled or dried. The energy density of these substrates is considerably higher than that of maize silage, although the energy yields per unit area are lower because the rest of the plant is left in the field.

4.1.2.2 Whole-crop cereal (WCC) silage

Almost all types of cereal, as well as mixtures of cereals, are suitable for producing whole-crop cereal silage, provided the cereals ripen at the same time. Depending on the local conditions, preference should be given to growing the type of cereal that is known to produce the highest dry matter yield. In most locations this is achieved with rye and triticale [4-5]. The harvesting technique is identical to that for maize; also in the case of WCC silage, the entire stalk is chopped and ensiled. Depending on the usage system, the harvest should take place at the time when the highest dry matter yields are obtained (one-crop system). For most cereal species, this is at the end of the milky stage/start of the doughy stage [4-7]. In the case of WCC silage, dry matter yields of between 7.5 and approaching 15 t DM/ha can be achieved, depending on location and year, which is equivalent, for 35% DM, to a fresh weight yield of 22 to 43 t fresh weight/ha [4-6].

The production of green rye (forage rye) silage is a technique commonly encountered in practice. Here, the rye is ensiled considerably earlier than in the case of WCC silage, in a two-stage harvesting process. This means that after being cut it is subsequently wilted for one or two days before being chopped and ensiled. Immediately after harvesting, the green rye is generally followed by a succeeding crop intended for energy generation (two-crop system). In view of the high level of water consumption, this method is not suitable for every location. Furthermore, if the DM content of the harvested crop is too low, problems can arise with silage-making (such as the escape of seepage or the ability to drive on the silo). The material data and gas yields of WCC silage are given at the end of this chapter.

4.1.2.3 Grass silage

As in the case of maize, growing and harvesting grass and the use of grass silage is well suited to mechanisation. Grass silage is harvested in a two-stage process; the wilted grass can be picked up with a short-chopping self-loading wagon or a forage harvester. Because of their superior size reduction performance, forage harvesters should be the preferred choice for grass silage for biogas use.

Grass silage can be produced from arable land in one or more years of a rotation system or from permanent grassland. The yields fluctuate greatly, depending on location, environmental conditions and intensity of grassland use. Given appropriate weather and climatic conditions, between three and five harvests per year are possible in intensive use. In this connection it is worth noting the high costs of mechanisation and the possibility of high nitrogen loads, which can give rise to problems during the digestion process. Grass silage can also be harvested from extensively managed nature conservation areas, although this results in low gas yields because of the high lignin content. The multiplicity of different ways of producing grass silage means that the fluctuation ranges of the material data and biogas yields found in the literature can extend well beyond the figures given in Table 4.3 and Table 4.4.

It should be pointed out in this connection that the emphasis should be on digestibility or degradability when producing grass silage for biogas plants. Care should therefore be taken that, where possible, the dry matter content should not exceed 35% DM. If the DM content is too high the proportion of lignin and fibre rises, as a result of which the degree of degradation, and therefore the methane yield, drop significantly in relation to the organic dry matter. While this grass silage can be included in the process, it is liable to cause technical problems (such as the rapid formation of floating layers or entanglement with agitator blades) because of the high dry matter content and sometimes long fibres.

4.1.2.4 Cereal grains

Cereal grains are particularly well suited for use in biogas plants as a supplement to the available substrate. Thanks to their very high biogas yields and rapid degradability, cereal grains are especially useful for the fine control of biogas production. The species of cereal used is inconsequential. In order to ensure rapid digestion, it is important for the cereal grains to be comminuted before being fed into the reactor (for example by grinding or crushing).

4.1.2.5 Beet

Thanks to its high rate of mass increase, beet (fodder beet or sugar beet) is well suited to cultivation as an energy crop. Sugar beet, in particular, has traditionally been an important crop in some regions. Because of steps taken to regulate the market, the quantity of beet used for sugar production is having to be reduced more and more. As the cultivation of sugar beet is founded on well known production techniques and has various agronomic advantages in its favour, the focus is increasingly turning to its utilisation for biogas.

Beet has special requirements in terms of soil and climate. To be able to produce high yields, it needs a rather mild climate and deep, humus-rich soils. The option of providing field irrigation on sites with light soil can help considerably to safeguard crop yields. Yields vary according to local factors and environmental conditions. In the case of sugar beet, they average around 50-60 t FM/ha. Yields of fodder beet are subject to further differences depending on variety; the yield from low dry-matter fodder beet is roughly 90 t FM/ha, for example, and that from high dry-matter fodder beet between 60 and 70 t FM/ha [4-8]. The yields from the leaf mass (tops) also differ according to the variety of beet. The ratio of root mass to leaf mass in the case of sugar beet is 1:0.8, while that for high dry-matter fodder beet is 1:0.5. Low dry-matter fodder beet has a root/tops ratio of 'only' 1:0.3-0.4 because of its high rate of mass increase [4-8]. The material data and gas yields of sugar beet are shown in Tables 4.3 and 4.4.

Two fundamental difficulties arise when sugar beet is used to produce biogas. Firstly, soil sticking to the beet has to be removed; when the beet is loaded into the digester the soil settles at the bottom and reduces the size of the digestion chamber. The first automated wet cleaning techniques for this purpose are currently under development. Secondly, storage proves difficult because of the low dry matter content of the beets. In practice, beet is combined with maize to make silage for biogas production, or it is ensilaged separately in plastic tubes or lagoons. The overwintering of beet and techniques for making use of this are undergoing trials.

Table 4.3: Material data of selected energy crops after [4-1], modified

Substrate		DM [%]	VS [% DM]	N [% DM]	P_2O_5 [% DM]	K_2O [% DM]
Maize silage	Δ	28-35	85-98	2.3-3.3	1.5-1.9	4.2-7.8
	∅	33	95	2.8	1.8	4.3
WCC silage	Δ	30-35	92-98	4.0	3.25	n. s.
	∅	33	95	4.4	2.8	6.9
Grass silage	Δ	25-50	70-95	3.5-6.9	1.8-3.7	6.9-19.8
	∅	35	90	4.0	2.2	8.9
Cereal grains	∅	87	97	12.5	7.2	5.7
Sugar beet	∅	23	90	1.8	0.8	2.2
Fodder beet	∅	16	90	n. s.	n. s.	n. s.

Δ: range of measured values; ∅: average

Table 4.4: Biogas yields of selected energy crops after [4-2],[4-6],[4-9],[4-10], modified

Substrate		Biogas yield [Nm^3/t substrate]	Methane yield [Nm^3/t substrate]	Specific methane yield on VS basis [Nm^3/t VS]
Maize silage	Δ	170-230	89-120	234-364
	∅	200	106	340
WCC silage	Δ	170-220	90-120	290-350
	∅	190	105	329
Cereal grains	∅	620	320	380
Grass silage	Δ	170-200	93-109	300-338
	∅	180	98	310
Sugar beet	Δ	120-140	65-76	340-372
	∅	130	72	350
Fodder beet	Δ	75-100	40-54	332-364
	∅	90	50	350

Δ: range of measured values; ∅: average

4.2 Substrates from the agricultural processing industry

Selected substrates from the agricultural processing industry are described in this section. These are all substances or co-products that arise from the processing of plants or parts of plants. The substances described are all taken from the Positive List of purely plant-based by-products as specified in EEG 2009, and serve as examples. Their material properties make them particularly suitable for producing biogas, given appropriate local conditions. It should be borne in mind that these substances have the characteristics of waste or are named in Annex 1 of the Ordinance on Biowastes (BioAbfV) (cf. Section 7.3.3.1). Consequently, the biogas plant requires corresponding approval and must satisfy the requirements of BioAbfV regarding the pretreatment and utilisation of digestates. When consulting the data summaries in the tables it must be taken into consideration that in practice the properties of the substrates are liable to fluctuate greatly and may be outside the ranges shown here. Essentially this is attributable to the production techniques of the principal products (for example different methods, equipment settings, required product quality, pretreatments, etc.) and fluctuating quality of the raw materials. The concentrations of heavy metals can also vary greatly [4-11].

4.2.1 Beer production

A variety of by-products arise from the production of beer, of which brewer's grains, with 75 %, account for the largest proportion. For each hectolitre of beer, approximately 19.2 kg of brewer's grains, 2.4 kg of yeast and tank bottoms, 1.8 kg of hot sludge, 0.6 kg of cold sludge, 0.5 kg of kieselguhr sludge and 0.1 kg of malt dust are produced as well [4-12].

Only brewer's grains are examined in closer detail in this section, because this constitutes the largest fraction. Nevertheless, the other fractions are equally well suited for use in biogas plants, with the exception of kieselguhr sludge. At present, however, only a proportion of the produced quantity is actually available for use, because the arising by-products are also put to other uses, for example in the food industry (brewer's yeast) or as animal feed (brewer's grains and malt dust). The material data and gas yields are summarised in Section 4.4.

Storage and handling are relatively unproblematic. If stored in the open, however, considerable energy losses and mould infestation occur rather quickly. In such cases, therefore, ensilage is preferable.

4.2.2 Alcohol production

Distillery spent wash (or vinasse) is a by-product from the production of alcohol from cereals, beet, potatoes or fruit. For each litre of alcohol produced, roughly 12 times the volume of spent wash is generated; at present, after being dried, this is mainly used as cattle feed or fertiliser [4-12]. The low dry matter content of spent wash in the fresh state means that in most cases it can be put to only limited use and is therefore barely worth transporting. In this connection the opportunities arising from the use of biogas in conjunction with the production of alcohol should be pointed out. Biogas is generated by digestion of the spent wash. The biogas can then be used in a combined heat and power unit to provide the process energy required for alcohol production, in the form of electricity and heat. This paves the way for the cascade use of renewable raw materials, which is a sustainable and resource-efficient alternative to the hitherto employed methods of utilising spent wash.

Details of the material data are given in Table 4.6 while details of the gas yields are given in Table 4.7 in Section 4.4.

4.2.3 Biodiesel production

Rapeseed cake and raw glycerol are by-products from biodiesel production. Thanks to their gas yields, which can be classified as high (Table 4.6), both of these substances are suitable for use as co-substrates in agricultural biogas plants. The gas yield from rapeseed cake is primarily determined by its residual oil content, which in turn is influenced by the settings of the oil presses and the oil content of the raw materials. Consequently, it is highly likely that variations in the gas yield from different rapeseed cakes will be encountered in practice. Roughly 2.2 t of rapeseed cake and 200 kg of glycerol are produced in the manufacture of one tonne of biodiesel [4-13]. However, there may be problems associated with the use of these by-products from biodiesel production, and these should be investigated very carefully in advance. The reason for this is that very high concentrations of hydrogen sulphide (H_2S) are formed in the biogas during the digestion of rapeseed cake [4-14]. This is due to the high protein and sulphur concentrations of the rapeseed cake. The problem with raw glycerol is that it sometimes contains more than 20 wt% of methanol, which, in high concentrations, has an inhibitory effect on methanogenic bacteria [4-15]. For this reason, only small quantities of glycerol should be added to the process.

Studies into the co-digestion of raw glycerol with energy crops and manure have shown that adding glycerol with a maximum mass fraction of 6% has a significant co-digestion effect [4-15]. This means that the mixture results in considerably more methane being produced than would be expected proportionately from the individual substrates. The same studies have also demonstrated that, if the added quantity of glycerol exceeds 8 %, there is no longer a positive co-digestion effect and it can even be expected that methane formation will be inhibited. To summarise, although the by-products from biodiesel production are well suited for use as co-substrates, it is advisable in practice to use them only in small proportions.

4.2.4 Potato processing (starch production)

In the production of starch from potatoes, a by-product known as potato pulp is produced in addition to organically contaminated wastewater. This pulp is primarily made up of skins (peel), cell walls and undecomposed starch cells that are left over after the extraction of starch. Approximately 240 kg of pulp is produced for each tonne of potatoes processed, along with 760 litres of potato juice and 400-600 litres of process water [4-16].

Currently, some of the pulp is passed on to farmers as cattle feed while the majority of the potato juice is applied to fields as fertiliser. However, use as animal feed accounts for only a small proportion of the arising quantity. Also, application of the juice on fields can lead to overfertilisation of soil and salinisation of groundwater. Therefore, alternative utilisation options are needed in the medium term.

One option is utilisation in biogas plants, because the by-products are easily digestible substrates. The material properties are given in Tables 4.6 and 4.7.

Although there are no special requirements regarding hygiene measures or storage, it should be taken into consideration that potato juice and process water have to be reheated for the digestion process if they are stored in tanks, which requires additional energy.

4.2.5 Sugar production

The processing of sugar beet to manufacture granulated sugar results in a variety of by-products, most of which are used as animal feed. These by-products include wet beet pulp, which is collected after the beets have been cut up and the sugar subsequently extracted, and molasses, which are left over after the sugar crystals have been separated from the thickened sugar syrup. Some of the beet pulp is mixed with molasses and dried by squeezing out the water to form dried molassed beet pulp, which is likewise used as animal feed [4-17, 4-18].

Apart from their use as animal feed, molasses are also used as a raw material in yeast factories or distilleries. Although this means that the available quantity is greatly limited, beet pulp and molasses are a highly suitable co-substrate for biogas production on account of their residual sugar content (cf. Annex 4.8, Table 4.9).

At present no particular hygiene requirements apply to storage or use. The pressed pulp is ensiled to enable it to be stored longer; this can be done either as a single substrate in plastic tubes or as mixed substrate with maize silage, for example. Molasses need to be stored in appropriate storage vessels. In view of the seasonal availability of sugar beet and its by-products (September to December), storage is necessary if pressed pulp and molasses are to be made available all year round.

Table 4.5: Standard biogas yields of purely plant-based by-products according to the Positive List of EEG 2009

Purely plant-based by-product	Standard biogas yield according to Section V. of Annex 2 of EEG	
	[kWh_{el}/t FM]	[Nm^3 CH_4/t FM]
Spent grains (fresh or pressed)	231	62
Vegetable trailings	100	27
Vegetables (rejected)	150	41
Cereals (trailings)	960	259
Cereal vinasse (wheat) from alcohol production	68	18
Grain dust	652	176
Glycerol from plant oil processing	1,346	364
Medicinal and spice plants	220	59
Potatoes (rejected)	350	95
Potatoes (pureed, medium starch content)	251	68
Potato waste water from starch production	43	12
Potato process water from starch production	11	3

Table 4.5: Standard biogas yields of purely plant-based by-products according to the Positive List of EEG 2009

Purely plant-based by-product	Standard biogas yield according to Section V. of Annex 2 of EEG	
	[kWh_{el}/t FM]	[Nm^3 CH_4/t FM]
Potato pulp from starch production	229	62
Potato peel	251	68
Potato vinasse from alcohol production	63	17
Molasses from beet sugar production	629	170
Pomace (fresh, untreated)	187	51
Rapeseed oil meal	1,038	281
Rapeseed cake (residual oil content approx. 15%)	1,160	314
Cut flowers (rejected)	210	57
Sugar beet press cake from sugar production	242	65
Sugar beet shavings	242	65

4.2.6 By-products from fruit processing

The processing of grapes or fruit into wine or fruit juice produces by-products known as pomace (or marc). As this still has a high sugar content, it is often used as a raw material in alcohol production. Pomace is also used as animal feed or as a raw material for making pectin. Each hectolitre of wine or fruit juice yields roughly 25 kg of pomace, and each hectolitre of fruit nectar around 10 kg of pomace [4-12]. The most important material data is listed in Tables 4.6 and 4.7.

Thanks to the preceding production process the pomace is not likely to contain any foreign matter or impurities, nor is there any need for hygienisation. If the substrates are intended to be stored for lengthy periods, ensilage is necessary.

4.3 Purely plant-based by-products according to EEG

The following provides a complete list of the purely plant-based by-products as specified in EEG (Positive List of purely plant-based by-products) with the statutory standard biogas yields (cf. Section 7.3.3.2). In order to allow comparison with the substrates described in this section, the statutory standard biogas yield (in kWh_{el}/t FM) is converted into a specific methane yield (Table 4.5). This assumes an electrical efficiency of 37% for the CHP unit and a net calorific value (lower heating value) of methane of 9.97 kWh/Nm^3 (see Table 4.5).

One fundamental problem is that the legislation gives only very approximate details of the material properties of the by-products. As the material properties of the by-products that affect the gas yield (in particular the dry matter content and residual oil content) extend across a very wide range in practice (cf. Section 4.2), there may be considerable deviations between the statutory gas yields and those that are actually attainable. This will inevitably result in overrating or underrating of the biogas yields obtained from the approved purely plant-based by-products.

4.4 Material data and gas yields of purely plant-based by-products

The tables below show material data and gas yields of selected substrates from Section 4.2. If available, both a range and an average value of the various parameters are listed. The breadth of the range of both the material data and the gas yields is sometimes considerable. It is therefore clear that, in real-world applications, the 'substrate quality' will vary very widely and be influenced by many production-related factors. The data presented here is intended as a guide. It should be noted that the results obtained in practice may in some cases be considerably higher or lower.

4.5 Prunings and grass clippings

The maintenance of parks and green verges by municipal authorities produces large quantities of green waste in the form of prunings and grass clippings. As this material arises on a seasonal basis, however, if it is to be made available all year round as a biogas substrate it has to be made into silage. This makes only limited sense, though, because of the widely dispersed arising of the material, which can mean that transport costs are excessively high. If the quantities involved are very small with intervals between deliveries, the material can also be added in the fresh state. Such material should be added extremely carefully, however, since the bacteria first have to adjust to the new substrate quality and disruption of the process cannot be ruled out if the quantities added are too

Table 4.6: Material data of selected purely plant-based by-products after [4-1],[4-2], [4-12], [4-17]

Substrate		DM [%]	VS [%DM]	N	P_2O_5 [%DM]	K_2O
Spent grains	Δ	20-25	70-80	4-5	1.5	n. s.
	∅	22.5	75	4.5	1.5	n. s.
Cereal vinasse	Δ	6-8	83-88	6-10	3.6-6	n. s.
	∅	6	94	8	4.8	n. s.
Potato vinasse	Δ	6-7	85-95	5-13	0.9	n. s.
	∅	6	85	9	0.73	n. s.
Fruit pomace	Δ	2-3	approx. 95	n. s.	0.73	n. s.
	∅	2.5	95	n. s.	0.73	n. s.
Raw glycerol	[4-1]	100	90	n. s.	n. s.	n. s.
	[4-15]	47	70	n. s.	n. s.	n. s.
Rapeseed cake		92	87	n. s.	n. s.	n. s.
Potato pulp	∅	approx. 13	90	0.5-1	0.1-0.2	1.8
Potato juice	Δ	3.7	70-75	4-5	2.5-3	5.5
	∅	3.7	72.5	4.5	2.8	5.5
Sugar beet shavings	Δ	22-26	95	n. s.	n. s.	n. s.
	∅	24	95	n. s.	n. s.	n. s.
Molasses	Δ	80-90	85-90	1.5	0.3	n. s.
	∅	85	87.5	1.5	0.3	n. s.
Apple pomace	Δ	25-45	85-90	1.1	1.4	n. s.
	∅	35	87.5	1.1	1.4	n. s.
Grape pomace	Δ	40-50	80-90	1.5-3	3.7-7.8	n. s.
	∅	45	85	2.3	5.8	n. s.

Δ: range of measured values; ∅: average

Table 4.7: Biogas yields of selected substrates from agricultural industry [4-1],[4-2],[4-12],[4-15], modified

Substrate		Biogas yield [Nm^3/t substrate]	Methane yield [Nm^3/t substrate]	Specific methane yield on VS basis [Nm^3/t VS]
Spent grains	Δ	105-130	62-112	295-443
	∅	118	70	313
Cereal vinasse	Δ	30-50	18-35	258-420
	∅	39	22	385
Potato vinasse	Δ	26-42	12-24	240-420
	∅	34	18	362
Fruit pomace	Δ	10-20	6-12	180-390
	∅	15	9	285
Raw glycerol	Δ	240-260	140-155	170-200
	∅	250	147	185
Rapeseed cake	∅	660	317	396
Potato pulp	Δ	70-90	44-50	358-413
	∅	80	47	336
Potato juice	Δ	50-56	28-31	825-1100
	∅	53	30	963
Sugar beet shavings	Δ	60-75	44-54	181-254
	∅	68	49	218
Molasses	Δ	290-340	210-247	261-355
	∅	315	229	308
Apple pomace	Δ	145-150	98-101	446-459
	∅	148	100	453
Grape pomace	Δ	250-270	169-182	432-466
	∅	260	176	448

Δ: range of measured values; ∅: average

large. Certain important material data together with the biogas yield and methane content are shown in Table 4.8. As a rule, prunings and grass clippings are not used for biogas generation but are sent for composting.

Apart from the above-mentioned logistical difficulties regarding ensilage, handling presents few problems. Undesirable matter, such as branches or stones, may have to be removed from the material before it is loaded into the biogas plant.

4.6 Landscape management material

The term landscape management material is activity-specific and covers materials from agricultural and horticultural activities, where these primarily serve the purpose of landscape management [4-20]. The areas where landscape management material arises include both nature conservation areas and areas where vegetation maintenance measures are undertaken. Trimmings and grass cuttings from protected biotopes, contract nature reserves and areas under agro-environmental or

Table 4.8: Material properties of prunings and clippings [4-12], [4-19]

Substrate	DM	VS	N	P_2O_5	Biogas yield	Methane yield	Specific methane yield on VS basis
	[%]	[% DM]	[% DM]		[Nm³/t FM]	[Nm³/t FM]	[Nm³/t VS]
Prunings and clippings	12	87	2.5	4	175	105	369

similar support programmes are therefore classed as landscape management material. Furthermore, roadside greenery, municipal prunings and clippings as well as prunings and clippings from public and private garden and park maintenance, sports field and golf course maintenance and from land alongside watercourses are also classed as landscape management material. In light of the fact that maintenance of nature conservation areas can usually only be carried out once a year, this material mostly has a high content of dry matter and lignin. This, in turn, is associated with lower gas yields and poor suitability for ensiling. Moreover, the use of such materials requires quite specific processing techniques or methods that are still extremely costly at present or are not yet state of the art. In contrast, the landscape management materials from vegetation maintenance measures, such as municipal grass cuttings or grass cuttings from sports fields and golf courses, have only little woody content and are thus more easily digestible.

In order to qualify for the landscape management bonus of 2 cents/kWh$_{el}$, more than 50 wt% of the materials used (with reference to the fresh mass) within one calendar year must come from landscape management (see also Section 7.3.3.2).

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Source: Kuhn (LWG)

4.8 Annex

Table 4.9: Overview of substrate characteristics

Substrate	DM [%]	VS [% DM]	N [a]	P_2O_5 [% DM]	K_2O	Biogas yield [Nm³/t FM]	CH_4 yield [Nm³/t FM]	Specific CH_4 yield [Nm³/t VS]
Manure								
Cattle slurry	10	80	3.5	1.7	6.3	25	14	210
Pig slurry	6	80	3.6	2.5	2.4	28	17	250
Cattle dung	25	80	5.6	3.2	8.8	80	44	250
Poultry manure	40	75	18.4	14.3	13.5	140	90	280
Horse manure w/o straw	28	75	n. s.	n. s.	n. s.	63	35	165
Energy crops								
Maize silage	33	95	2.8	1.8	4.3	200	106	340
WCC silage	33	95	4.4	2.8	6.9	190	105	329
Green rye silage	25	90				150	79	324
Cereal grains	87	97	12.5	7.2	5.7	620	329	389
Grass silage	35	90	4.0	2.2	8.9	180	98	310
Sugar beet	23	90	1.8	0.8	2.2	130	72	350
Fodder beet	16	90	n. s.	n. s.	n. s.	90	50	350
Sunflower silage	25	90	n. s.	n. s.	n. s.	120	68	298
Sudan grass	27	91	n. s.	n. s.	n. s.	128	70	286
Sweet sorghum	22	91	n. s.	n. s.	n. s.	108	58	291
Green rye[b]	25	88	n. s.	n. s.	n. s.	130	70	319
Substrates from processing industry								
Spent grains	23	75	4.5	1.5	0.3	118	70	313
Cereal vinasse	6	94	8.0	4.8	0.6	39	22	385
Potato vinasse	6	85	9.0	0.7	4.0	34	18	362
Fruit pomace	2.5	95	n. s.	0.7	n. s.	15	9	285
Raw glycerol[c]	n. s.	n. s.	n. s.	n. s.	n. s.	250	147	185
Rapeseed cake	92	87	52.4	24.8	16.4	660	317	396
Potato pulp	13	90	0.8	0.2	6.6	80	47	336
Potato juice	3.7	73	4.5	2.8	5.5	53	30	963
Pressed sugar beet pulp	24	95	n. s.	n. s.	n. s.	68	49	218
Molasses	85	88	1.5	0.3	n. s.	315	229	308
Apple pomace	35	88	1.1	1.4	1.9	148	100	453
Grape pomace	45	85	2.3	5.8	n. s.	260	176	448
Prunings and grass clippings								
Prunings and clippings	12	87.5	2.5	4.0	n. s.	175	105	369

a. N concentrations in digestate, excluding losses in storage
b. wilted
c. Results vary greatly in practice, depending on the method used for biodiesel production

Operation of biogas plants

5

The economic efficiency of a properly planned biogas plant is determined by the availability and capacity utilisation of the process as a whole. Key factors are the functionality and operational reliability of the technology employed, and consistently high degradation performance within the biological process.

As the operation of technical facilities is subject to inevitable malfunctions, appropriate tools must be on hand in order to detect such malfunctions and identify and rectify the fault. Process control is always performed in interaction with the personnel, although the degree of automation can vary extremely widely. If monitoring and control algorithms are automated, the benefits are that the system is constantly available and a degree of independence from expert personnel is achieved. The remote transmission of data also decouples the need for staff presence at the plant from process monitoring. The downside of extensive automation is the resultant additional cost. As these advantages and disadvantages have different weighting depending on the plant specifications, there cannot be assumed to be such a thing as a standardised set of instrumentation and control equipment for biogas plants. The instruments used need to be adapted to the specific conditions in each case.

The following sections first examine the measured variables that can be used to observe the biological process.

The descriptions relate to wet fermentation plants. Any different special feature applicable to batch type (dry) digesters is pointed out in each case.

5.1 Parameters for monitoring the biological process

Monitoring and controlling the biological process is a challenge. The process objective of anaerobic digestion in the agriculture sector is usually the achievement of a constant methane production rate. The most commonly used method involves a continuous (or semi-continuous) stirred-tank reactor (CSTR). In this case constant methane production is achieved when steady-state operation is established. In the steady state, changes to process variables are zero and the maximum process-specific conversion rates are achieved [5-26].

$$V\frac{dS}{dt} = Q_{in} \cdot S_o - Q_{out} \cdot S + V \cdot r_s = 0$$

Equation 5.1: Steady-state operation (Q: volumetric flow rate ($l \cdot d^{-1}$) (input, output), V: reaction volume (l), r_s: reaction rate $g \cdot (d \cdot l)^{-1}$, S_o: concentration substrate inflow ($g \cdot l^{-1}$), S: concentration substrate outflow ($g \cdot l^{-1}$))

Variables such as the organic loading rate, retention time, achievable degree of degradation and gas production rate are therefore predetermined by the sizing of the plant and the chosen substrate. The plant operator must ensure that these variables are kept constant as much as possible. However, the steady state is virtually unattainable in practice because process disturbances inevitably occur (for example changes to substrate properties, malfunctions such as the failure of pumps, or the introduction of disinfectants etc.). These disturbances lead to deviations from the desired state, which need to be detected so that the cause can be identified and rectified.

Such deviations from the steady state can be detected directly by means of a material flow balance. In practical application, however, it is difficult to measure the material composition of the input and output precisely and in many cases even to measure the quantity of substrate actually loaded and the amount of gas produced, so it is impossible to achieve a precise closed mass balance at reasonable expense. For this reason, partial solutions adapted to the specific circumstances are used in many plants. These are not always sufficient to ensure the running of a stable process.

The measured variables available for evaluation of the biological process and most commonly used in practice are described in the following.

5.1.1 Biogas production rate

The biogas that is generated is a crucial measured variable as a metabolic product and a target variable. The biogas production rate is the quantity of gas produced per unit of time (e.g. d^{-1}), and with a known feed volume and substrate composition serves as the basis for calculating the specific biogas production (substrate-specific and volume-specific). Measuring the biogas production rate is essential for balancing the metabolic processes and assessing the efficiency of the methanogenic population.

When equipment is being installed to detect gaseous flows, attention must be paid to the positioning of the sensors. If the process states of individual digesters need to be observed, their gas production rates must also be recorded separately. If the digesters have membrane roofs, in order to calculate the gas production rate it is necessary to take account of the storage volume, which can be done by recording the filling level (e.g. by cable-extension transducer), internal pressure and temperature in the gas space. Sensors in the gas space must satisfy explosion protection requirements and should be resistant to corrosion and high levels of moisture. As membrane roofs also serve the purpose of storing biogas, measuring the gas production rate and available storage volume is also particularly important for controlling CHP unit output.

With regard to the measurement of gas flows in pipes, care must be taken that the inlet sections specified by the manufacturer are in place in order to produce laminar flows. Measuring instruments with moving parts in the biogas stream are susceptible to faults because of the impurities carried in the biogas stream. Instruments based on the thermal and fluidistor measuring principles are used in the biogas sector, as well as vortex flowmeters.

5.1.2 Gas composition

The composition of the biogas can be used to assess a variety of circumstances. The individual constituents and their significance for the process are explained briefly in the following.

5.1.2.1 Methane

The proportion of methane in the biogas serves to evaluate the state of methanogenic biocoenosis. The methane production rate can be calculated in connection with the gas production rate: if the methane production rate drops significantly despite a constant feeding rate, it can be assumed that the methanogenic archaea are inhibited. Measuring points must be provided in the individual digesters in order to evaluate methane productivity. In biogas technology, methane concentrations are measured with infrared sensors or thermal conductivity sensors.

For operation of the combined heat and power unit it is important that the content of methane in the gas does not fall below 40-45%, because then the engines are no longer able to utilise the biogas.

5.1.2.2 Carbon dioxide

Carbon dioxide is formed during the hydrolysis/acidogenesis phase and in the course of methane formation. It dissolves in water, thus forming the important hydrogen carbonate buffer. If the methane/carbon dioxide ratio in the biogas falls without the substrate composition having been changed, the cause may be a higher rate of acid formation compared with methane formation. The equilibrium of mass flows in the degradation process is then disrupted. This may be caused by variation of the input quantities or inhibition of the methanogenic population.

Carbon dioxide, like methane, is measured with infrared sensors or thermal conductivity sensors.

5.1.2.3 Oxygen

Oxygen should only be detectable in the biogas if it is added for the purposes of biological desulphurisation. In that case, oxygen measurement can be used to adjust the oxygen content required for desulphurisation. Oxygen can be measured with electrochemical sensors and paramagnetic sensors.

5.1.2.4 Hydrogen sulphide

The manufacturers of combined heat and power units specify limits for the concentration of hydrogen sulphide, because its oxidation products have highly corrosive properties. The primary purpose of measuring it is therefore to protect the CHP unit.

High concentrations of hydrogen sulphide do not affect the methanogenic archaea until the concentrations reach the percent range (roughly 20,000 ppm), which rarely occurs in agricultural biogas plants. Hydrogen sulphide is measured with electrochemical sensors.

5.1.2.5 Hydrogen

Hydrogen is an important intermediate product in the process of methane formation; it is mostly released during acidogenesis and acetogenesis, before it is converted into methane. There have been several attempts to use the hydrogen concentration in the biogas to detect process disturbances. In this connection it is particularly significant that theoretically the formation of acetic acid from longer-chain fatty acids and the utilisation of hydrogen to form methane can only take place together within a narrow concentration range. The suitability of this parameter is disputed, as it does not always prove possible to establish an unambiguous correlation between the hydrogen concentration in the biogas and disruption to the process. The hydrogen concentration in the biogas can be measured easily with the aid of electrochemical sensors. To date, little has been done to investigate the suitability of the hydrogen partial pressure in the fermentation substrate as a control parameter.

Most manufacturers of gas analysis equipment in the biogas sector offer modular devices, which enable the user to choose the type of sensors and the number of measuring points. With regard to electrochemical sensors it must be borne in mind that they 'wear out' and exhibit greater drift than infrared sensors, for example. The sensors must be regularly calibrated.

5.1.3 Temperature

As a general rule, the rate of reaction increases with rising temperature. Biological processes, however, have optimum temperatures, because organic structures (e.g. proteins) are liable to become unstable as temperatures rise and can lose their functionality. When anaerobic processes are used in technical applications, they are essentially divided into two temperature ranges:

- mesophilic range approx. 37 to 43 °C
- thermophilic range approx. 50 to 60 °C

As very little heat is produced in anaerobic fermentation (except in some plants fed with energy crops), the substrate must be heated to reach fermentation temperature. It is important that the temperature is kept constant. The thermophilic process, in particular, is sensitive to temperature fluctuations.

In some cases plants utilising maize silage experience temperature rises that can make cooling necessary.

The sensors used to measure the temperature should be installed at various heights so that stratification and inadequate mixing can be detected. Care should also be taken that the sensors are not installed in dead zones or too close to the temperature stabilisation equipment. Resistance sensors (e.g. PT 1000 or PT 100) or thermocouples are suitable for measuring the temperature.

5.1.4 Input volume and fill levels

In order to ensure balancing of the degradation processes, precise measurement of the quantity of substrate added is absolutely essential. In addition to liquid substrates, in some cases solids are also fed into the digesters, so different measuring systems are used.

The best way of measuring solids is to weigh them. This is done using wheel loader scales or weighing equipment in the loading systems. The latter are more accurate, and are easier to integrate into automated process control systems. The weighing equipment uses pressure sensors, which require the use of 'floating' containers. Soiling in the vicinity of these sensors must therefore be avoided, as must topping up the holding vessels during the loading process.

For liquid substrates, flow-measuring devices can be installed on the pipes, or if the plant has pre-pits the infeed volume can be measured with fill-level meters.

Fill levels (also in digesters) can be determined using pressure sensors (hydrostatic pressure in the digester) or by measuring the distance to the surface ultrasonically or by radar. Regarding the choice of sensors, attention should be paid to corrosion resistance and insensitivity to soiling, especially since in-situ maintenance is costly and difficult. A further consideration when choosing and positioning the sensors is that particular operating states such as the build-up of sediment (e.g. sand) on the bottom of the digester, foaming, sulphur deposits in the gas space etc. must not be allowed to affect measurements. Explosion protection must also be ensured.

The devices that have proved best for measuring flow are those that work without moving parts in the measured medium. Inductive and capacitive sensors are the most common types, although in individual cases ultrasound and thermal conductivity sensors are also used. Depending on the methodology, provision must be made for an adequate inlet run to the sensors in order to produce laminar in-pipe flow. Flow measurement has the advantage that, if more than one feeding line can be routed through one pipe thanks to a favourable valve arrangement, several feeding lines can be monitored with one measuring device.

5.1.5 Substrate characterisation

As well as the quantity of substrate, it is also necessary to know the concentration and composition of the substrate in order to obtain a mass balance.

Sum parameters such as the total solids (TS) content (= dry matter content, DM) and volatile solids (VS) content are used to determine the concentration. For liquid substrates it is also possible to use the chemical oxygen demand (COD), and total organic carbon (TOC) is also occasionally used. Only the first two parameters mentioned are relevant in practice.

The first step towards determining the biodegradable fraction of the substrate is establishing the water content or total solids content. To do this, a sample is dried to constant weight at 105 °C in the laboratory. In the meantime there are also new sensor developments on the basis of microwaves and near infrared which determine the content online within the process.

One criterion for assessing degradability is obtained by determining the proportion of organic constituents in the dry matter. The volatile solids content is a sum parameter obtained by burning away the dried sample at 550 °C. The resultant loss of mass, referred to as the loss on ignition, corresponds to the amount of organic dry matter. This value is a sum parameter but it tells you nothing about the degradability of the substance under test nor the amount of biogas expected to be produced. In the literature there are guide values that can be used to estimate the expected gas production volume if the substrate and its volatile solids content are known. Drying the sample eliminates volatile substances (for example steam-volatile acids), so these substances do not figure in the analytical result. Especially when substrates are acidified (as in the case of silages, for example), this can lead to considerable errors in estimation of gas potential. Weissbach therefore developed a correction method that takes account of the volatile substances. This method is significantly more complex, however [5-18].

The residue left over after the sample is ignited is known as the residue on ignition; this represents the proportion of inert constituents in the substrate. If the substrates contain large quantities of sand, the residue on ignition can be used to estimate the sand content, and in combination with sieving the grain size distribution of the sand can be estimated as well [5-19]. The sand content is important because of its abrasive properties and its sedimentation in the digester in the case of some substrates (e.g. poultry manure).

A more precise characterisation of the substrate can be obtained by classifying the substrate constituents according to Weende (crude fibre, crude protein, crude lipids and nitrogen-free extract, which in combination with digestibility quotients describe the suitability of organic substances for use as animal feed; see also 2.3.4.1), or according to van Soest (hemicellulose, cellulose and lignin). These constituents determine the nature of the intermediate products formed. If there are sudden changes to the substrate, therefore, sudden accumulations of intermediate products can arise which cannot be degraded because the corresponding bacteria population is not present or does not exhibit sufficiently high growth rates. Animal feed analysis can also be used to determine the expected gas yield more accurately than on the basis of the volatile solids content. This method of analysis is therefore also better for assessing the quality of substrates.

Determination of the concentration of the substrate is essential for reliable mass balancing; supplementary determination of the composition of the substrate can also be used to assess the quality of the substrate.

5.1.6 Determination of the concentration of organic acids

Organic acids are an intermediate product in the formation of biogas. The acids dissociate in aqueous solution, depending on the pH value. The constituents can be calculated as follows:

$$f = \frac{10^{pK_S - pH}}{1 + 10^{pK_S - pH}}$$

Equation 5.2: Calculation of the dissociation factor according to [5-20] (f: dissociation factor, pK_S: negative common logarithm of the acidity constant, pH: pH value)

In the steady state the rates of acid formation and transformation are identical, so the concentration in the digester is constant. If there is a higher rate of acid formation and/or degradation is inhibited, the acids accumulate and the concentration rises. Bacterial growth is dependent on substrate concentration, as indicated by the principles described by Monod, so an increase in acid concentration results in a higher rate of growth and within certain limits, the process stabilises itself. However, if the rate at which the acids are formed exceeds the capacity of the acid-degrading microorganisms for a sustained period, the concentration continues to rise. If no intervention takes place, the acids accumulate to the point at which the buffer capacity of the fermentation substrate is consumed and the pH value drops. Acid degradation is inhibited when the concentration of the undissociated proportion of the acids is at an elevated level, and this effect is reinforced as the pH value falls.

It is difficult to specify a limit value for a maximum permissible acid concentration in the steady state because the concentration that establishes itself is dependent on factors such as dwell time, the substrate used and the presence of inhibitory substances.

As a guide, several figures quoted in the literature are listed in Table 5.1.

As far as assessment of the process is concerned, it is imperative for acid concentration to remain constant. If the acid concentration rises, it is essential to exercise caution. Process models are needed in order to evaluate processes under dynamic conditions, i.e. with changing acid concentrations.

As well as the sum parameter of the acids, the concentrations of individual acids can provide additional information. If the spectrum reveals that the longer-chain acids are increasing faster than acetic acid, the transformation of these acids into acetic acid is being inhibited. The transformation of longer-chain acids into acetic acid is an endogenous process, occurring only when hydrogen concentrations are low, and what is more the growth rate of these microorganisms is low. Because of these unfavourable circumstances, this sub-process can become a bottleneck in the process. Correspondingly, higher concentrations of propionic acid are degraded only slowly.

In some publications reference is made to the ratio of acetic acid and propionic acid as a parameter for assessing the process, but to date it has not been possible to establish a generally applicable pattern.

There are various methods for determining the concentration of organic acids (currently for these analyses it is necessary to take a sample for laboratory analysis):

Table 5.1: Limit values for max. permissible acid concentration

Author	Limit value Concentration Acetic acid equivalents ($mg \cdot l^{-1}$)	Method, comments
[5-20]	200 undissociated acid	Stirred-tank reactor operated under thermophilic conditions with upstream hydrolysis reactor
[5-20]	300 (adapted biocoenosis) undissociated acid	Stirred-tank reactor operated under thermophilic conditions with upstream hydrolysis reactor
[5-21]	30-60 undissociated acid	Continuous stirred-tank reactor (CSTR) operated under mesophilic conditions
[5-2]	80 (increase in inhibition above 20) undissociated acid	No data
[5-22]	100-300 total acid	Sewage sludge fermentation, normal process state
[5-22]	1,000-1,500 total acid	Sewage sludge fermentation, normal, during start-up phase
[5-22]	1,500-2,000 total acid	Sewage sludge fermentation, risk of process failure, discontinue loading or add alkali
[5-22]	4,000 total acid	Sewage sludge fermentation, little chance of recovery in short term
[5-23]	< 1,000 total acid	Stable fermentation

- as a sum parameter (e.g. steam distillation in accordance with DIN 38414-19)
- as a spectrum (e.g. gas chromatography) or
- calculated on the basis of parameters determined empirically from the result of titration (VOA – volatile organic acids)

Determination of the sum parameter according to DIN 38414-19 has become rare on account of the increasingly widespread use of the VOA value. This method is more complex than determination of the VOA value because of the need to distil the steam-volatile acids, but it is also more precise.

Determination of the acid spectrum by gas chromatography (liquid chromatography is another possibility) requires complex measurement technology and experience with the substrate. The sum of the acids is not the only result; it is also possible to determine the concentrations of the individual fractions of the lower fatty acids. This is the most accurate of the above-mentioned methods.

In recent years the VOA value has become established as a parameter that is easy to determine [5-24]. The VOA value is mostly used in combination with the TAC value (VOA/TAC).

The VOA/TAC value is determined by titration. The origin of the abbreviation TAC is not entirely clear; various designations are given in the literature, none of which are truly accurate or correct renderings of the term. The TAC value stands for the 'consumption A' of 0.1 N sulphuric acid during the titration of a sample to pH 5. The amount of acid consumed is converted into a corresponding carbonate concentration (mg $CaCO_3$/l). If titration is then continued to pH 4.4, the concentration of organic acids can be deduced from the 'acid consumption B'. The formulae used for calculating acid concentration are of an empirical nature:

Sample amount: 20 ml (centrifuged)
TAC: consumption A x 250 [mg/l $CaCO_3$]
VOA: ((consumption B x 1.66) - 0.15) x 500 [mg/l HAc]

The VOA/TAC ratio is often used for process evaluation. Bear in mind, however, that since the formulae are empirical the analytical results from different processes are not comparable. Experience shows that the VOA/TAC value should be no greater than 0.8. Here too, though, there are exceptions, and as in the case of acids, problems can be detected by observing changes to the value. The method of calculation used has to be taken into account when assessing the results.

5.1.7 pH value

Biological processes are heavily dependent on the pH value. The optimum pH range for generating methane is within a narrow window between approximately 7 and 7.5, although the gas can also form above and below this range. In single-stage arrangements, as a rule, a pH value in the optimum range is established automatically, because the bacterial groups form a self-regulating system. In a two-stage process the pH value is considerably lower in the hydrolysis stage, normally between 5 and 6.5, since that is where the acid-forming bacteria have their optimum. In the methanogenic stage the pH value is raised back up to the neutral range again thanks to the buffer capacity of the medium and the degradation activities.

The pH value controls the dissociation equilibria of important metabolic products such as ammonia, organic acids and hydrogen sulphide. The buffer capacity of the medium (mainly hydrogen carbonate and ammonium) normally guarantees a stable pH value. If major changes do in fact occur and the pH value shifts out of its optimum range, this is usually a sign of serious disturbances and action should be taken immediately.

5.1.8 Concentrations of trace elements

Trace elements are mineral substances occurring in very low concentrations. Plants that are run exclusively on energy crops (and those using spent wash/vinasse) are susceptible to process disturbances that can be corrected by the addition of trace elements. Declining gas production and rising acidity levels are indicative of these disturbances. These phenomena are not observed in plants operated on a slurry basis. So far it has not proved possible to identify the precise mechanisms and the substances that actually cause the limiting effect, but the concentrations of trace elements in energy crops are significantly below those that have been detected in various types of manure [5-26].

A number of suppliers offer appropriately adapted mixtures of trace elements for the purpose of process optimisation. There are indications that the addition of iron ions in the form of iron chloride or iron hydroxide, as often used for desulphurisation, can have a stabilising effect. This is put down to the fact that the sulphide forms poorly soluble metal sulphides, thus restricting the availability of the trace elements. If the sulphide is mostly bonded by the iron, the availability of the other metals rises. The table below shows guide values for the various elements.

One method that indicates guide values and describes the addition of trace elements was registered for a patent [5-28].

When adding trace elements it should be borne in mind that these are heavy metals which can have an inhibitory effect in high concentrations and are classed as pollutants. Whatever the case, the elements must be added according to the principle of as much as necessary but as little as possible.

5.1.9 Nitrogen, ammonium, ammonia

When organic substances that contain nitrogen are broken down, the nitrogen is converted into ammonia (NH_3). Ammonia is dissociated in water, forming ammonium.

Table 5.2: Guide values for trace elements

Element	Guide values [5-28] mg/kgTS	Guide values [5-27] Concentration mg/l
Cobalt	0.4-10 (optimum 1.8)	0.06
Molybdenum	0.05-16 (optimum 4)	0.05
Nickel	4-30 (optimum 16)	0.006
Selenium	0.05-4 (optimum 0.5)	0.008
Tungsten	0.1-30 (optimum 0.6)	
Zinc	30-400 (optimum 200)	
Manganese	100-1500 (optimum 300)	0.005-50
Copper	10-80 (optimum 40)	
Iron	750-5000 (optimum 2400)	1-10 [5-29]

Nitrogen is necessary for building cell structure and is therefore a vital nutrient.

On the other hand it has been shown that high concentrations of ammonia/ammonium in the substrate have an inhibitory effect on methanogenesis. There is still no single, agreed opinion on the precise mechanisms that cause this inhibition, but it is obvious that the bacteria are able to adapt to higher concentrations. This makes it difficult to give clear indications of limit values, as the reaction to elevated ammonia/ammonium concentrations is process-specific.

There is much to suggest that the inhibitory effect comes from the undissociated fraction, in other words from the ammonia, and that a dependency emerges between the inhibitory effect and concentration, temperature and pH value. The consequence, confirmed in practice, is that thermophilic plants respond more sensitively to high ammonium concentrations than mesophilic plants. The correlation is shown by the equation below.

$$c_{NH_3} = c_{NH_4} \cdot \frac{10^{pH}}{e^{\frac{6344}{273+T}} + 10^{pH}}$$

Equation 5.3: Calculation of ammonia concentration according to [5-30] (c_{NH_3} concentration of ammonia ($g \cdot l^{-1}$), c_{NH_4} concentration of ammonium ($g \cdot l^{-1}$), T temperature (°C))

Figure 5.1 depicts the dissociation equilibrium and inhibition as explained in [5-2]. While it would no doubt be wrong to transfer the absolute values for inhibition to all processes (see below), the general principle of the progression of the inhibitory effect is transferrable.

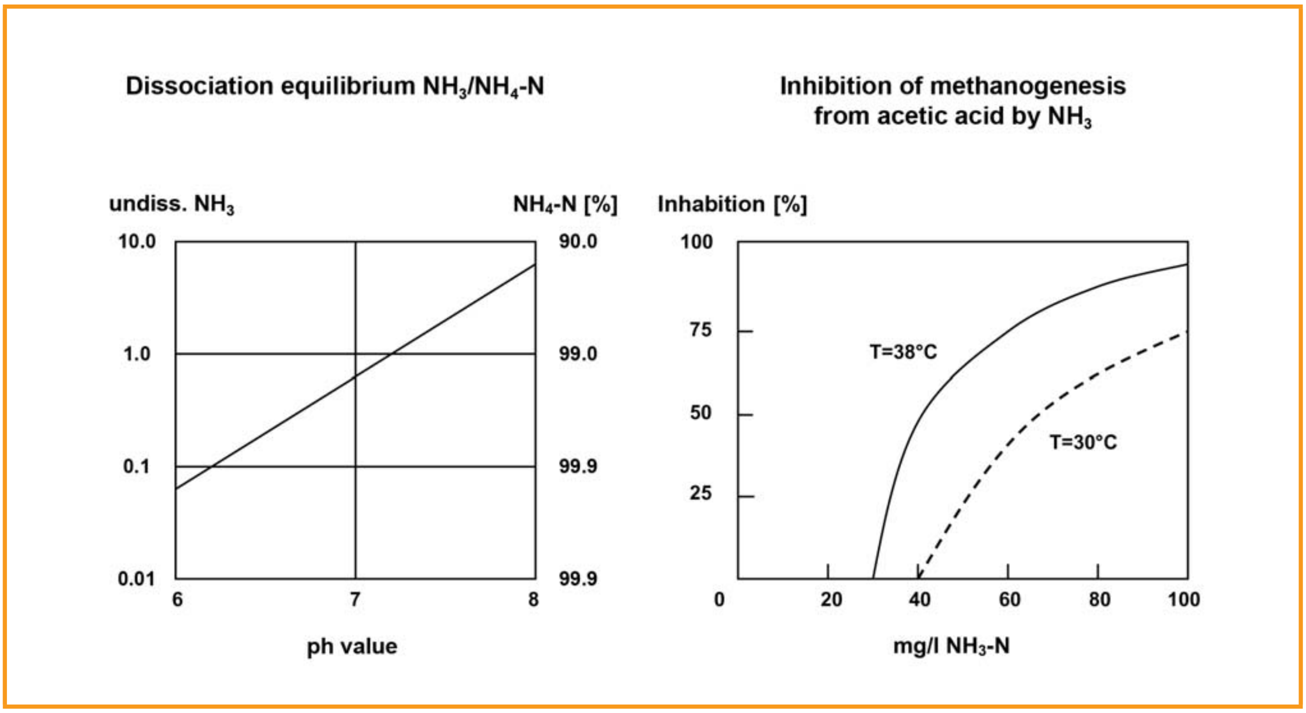

Figure 5.1: Inhibition of methanogenesis from acetic acid by NH_3 (as per [5-2])

Table 5.3 summarises various publications dealing with the topic of ammonia/ammonium inhibition. It is clearly apparent that the figures vary widely, which underlines the fact that no universally applicable statements can be made about ammonia/ammonium inhibition.

Table 5.3: References in the literature to inhibitory concentrations of ammonia

Author	Concentration		Comments
[5-33]	> 3000 mg · l^{-1} NH_4		Inhibitory effect
[5-32]	> 150 mg · l^{-1} NH_3		Inhibitory effect
[5-31]	500 mg · kg^{-1} NH_3 1200 mg · l^{-1} NH_3		Stable operation, elevated acid concentrations,inhibitory effect
[5-30]	< 200 mg · l^{-1} NH_3		Stable operation
[5-21]		Degree of degradation %	Stable operation in all cases, but reduced degradation performance and elevated acid concentration
	106 mg · l^{-1} NH_3	71	
	155 mg · l^{-1} NH_3	62	
	207 mg · l^{-1} NH_3	61	
	257 mg · l^{-1} NH_3	56	
[5-34]	> 700 mg · l^{-1} NH_3		Inhibitory effect

In connection with elevated ammonium concentrations, [5-21] reports elevated acid concentrations at the same time; this correlation can also be observed in practice. The higher acid concentrations are indicative of a growth rate close to the maximum for the acid-consuming populations. Despite these unfavourable conditions stable operation is possible, although greater caution is required in the event of load fluctuations because the process is no longer able to cushion them by increasing metabolic activity. In certain circumstances gas production may then remain constant for a while, but acid enrichment takes place in the fermentation substrate. High ammonium concentrations act as a buffer, so higher concentrations of organic acids do not necessarily lead to changes in the pH value.

Given a long period of time for adjustment (up to a year), the microorganisms are able to adapt to high ammonia concentrations. Studies with fixed-bed reactors have shown that they are able to adapt better to higher concentrations than stirred-tank reactors. From this it can be concluded that the age of the bacteria is a factor in adaptation; it follows, therefore, that long residence times in stirred-tank reactors would be a strategy for mastering the inhibitory effect.

To date there is no clear knowledge of where the limits lie with regard to ammonia concentration, organic loading rate and dwell time. Adjustment takes time, and is associated with fluctuating degradation performance. The adjustment process is therefore also associated with economic risk.

Ammonia/ammonium can be measured with ion-selective probes or by means of cuvette tests, or conventionally by distillation and titration (DIN 38406, E5). The field use of probes is not widespread; laboratory analysis of samples is more common. As the limiting concentration is process-specific, the ammonia concentration on its own offers little information about the state of the process as a whole. Determination of the ammonium content should always be accompanied by determination of the pH value so that ammonia content can be gauged. If disturbances occur, this can help to identify the cause.

5.1.10 Floating sludge layers

The formation of layers of floating sludge or scum can present a problem in plants with fibrous substrate. Sludge layers form when fibrous material floats up and mats on the surface, forming a solid structure. If the layer is not broken by suitable agitators it can grow to a thickness of several metres, in which case it has to be removed manually.

That said, a certain stability in the surface structure is undoubtedly desirable in plants that desulphurise through the addition of air in the gas space. In this case the surface serves as a colonising area for the desulphurising bacteria.

Treatment of the floating sludge layer thus becomes an optimisation problem, which the plant operator generally deals with by keeping the layer under observation through the inspection window. As yet there is no measuring technology that monitors the formation of floating sludge layers.

5.1.11 Foaming

Foaming is the consequence of reduced surface tension, brought about by surface-active substances. The precise cause of foaming in the biogas formation process is not known. It occurs in sub-optimum conditions (for example spoiled silage, or overload phenomena in combination with a high concentration of ammonium). It is possible that the cause might be enrichment of surface-active intermediate products or bacterial groups in the process, combined with vigorous gas formation.

Foam can be a serious problem if the gas pipes become blocked and the pressure in the digester forces the foam out of the pressure relief devices, for example. Defoaming agents are useful as a quick fix, but in the long term the cause has to be identified and eliminated.

In terms of measuring technology, foaming can be detected by a combination of various fill-level measuring devices. A pressure sensor will not respond to foam, for instance, whereas ultrasound sensors detect foam as a change to the surface. The difference between the two systems tells you the depth of the foam.

5.1.12 Process evaluation

Process evaluation is carried out by analysing and interpreting measured values. As already established, balancing of the mass flows is the most reliable method of describing the process. In practice, however, this is not economically viable because of the cost and complexity involved. Furthermore, various particularities arise in practice in relation to the recording of measured values, so the differences between laboratory analysis and sensors installed online in the process are examined briefly below. All lab analyses require representative sampling to have taken place, after which the samples have to be transported to a laboratory. Analyses of this type are time-consuming and costly, and there is a delay before the results are available. Sensors that take measurements directly within the process, on the other hand, have a considerably higher measurement density, and the measured values are available immediately. Cost per measured value is significantly lower, and the data can easily be integrated into process automation.

Unfortunately, at this time the measured variables required for mass balancing cannot be metered with online sensors, so supplementary laboratory analyses are indispensable. The necessary variables and their availability are summarised in the table below.

Constant monitoring of all the variables listed here is too costly, and in many plants it is unnecessary. Partial solutions need to be found in order to meet the requirements of each specific plant. The criteria for control and the required measurement technology are:

- permissible process deviation
- intended degree of automation
- process properties.

Table 5.4: Measured variables and their availability

Measured variables for mass balancing	Available online
Input composition	TS determination under development, all other parameters laboratory analysis
Intermediate products (organic acids)	Laboratory analysis necessary
Output quantity	Available online
Composition of fermentation residue	TS determination under development, all other parameters laboratory analysis
Quantity of gas generated	Available online
Composition of biogas	Available online

Early detection of critical process states (acid accumulation, with subsequent inhibition and reduced gas production) is a minimum requirement for every process monitoring system in order to be able to avoid serious performance losses. Furthermore, monitoring should be sufficiently accurate to allow closed-loop control of gas production – utilisation of the capacity of the CHP unit must be ensured.

The degree of automation required is undoubtedly dependent on the size of the plant: the larger the plant, the less clear the various sub-processes become, and automation becomes essential. As the level of automation increases a certain degree of independence from expert personnel is achieved, remote monitoring can be implemented and human error can be reduced.

With regard to the process properties it should be stated that the risk of overloading the process is more likely in plants that operate with a high organic loading rate and/or short residence times, have high concentrations of inhibitory substances or use changing substrate mixtures. This should be countered by appropriate investment in process monitoring.

An estimation of the expenditure required for process monitoring is given in Section 5.3.

5.2 Plant monitoring and automation

Various options are available for monitoring, supervising and controlling processes and plants. The bandwidth of applications commonly used in practice extends from operating logs to fully automated data acquisition and control systems (Fig. 5.2). When it comes to deciding what degree of automation should be put in place, consider the level of availability of the process control system that you aim to achieve, the extent to which it should be possible to operate the plant independently of expert personnel, and which process properties necessarily require automation.

The availability of process control increases with the degree of automation, as does plant availability. In highly automated systems, data logging and steady operation are therefore also ensured at weekends and on public holidays. Higher levels of automation also make operation of the plant less dependent on the constant presence of operating personnel. With regard to the process properties it should be said that the number of process parameters needing to be monitored also rises as the size of the plants increases. As of a certain size, automation of the processes is indispensable. The risk of serious disturbances increases in plants with a high organic loading rate and plants with a tendency toward paucity (e.g. trace elements) or inhibitory substances. Under these circumstances automated data logging and process control offer the opportunity of detecting and correcting process disturbances in good time.

Very simple solutions such as the recording of data in operating logs and manual or timed control of sub-processes are still common in small, slurry-based plants. However, if the data is not subsequently entered in electronic form, it frequently proves impossible to ensure that the data can be evaluated or fully documented. Optimisation of the processes becomes correspondingly more difficult.

Various automation solutions are available, depending on the requirements of the application. The term 'automation' covers open-loop control, closed-loop (feedback) control and visualisation. The prerequisite for automation is that the process must be monitored, i.e. the available process data must be continuously recorded and stored.

In most cases, programmable logic controllers (PLCs) are used for process control in biogas plants. These devices deal with many automation tasks in the process environment. For biogas plants, these include all control tasks involving the need to monitor purely technical matters such as pump running times, loading intervals, stirring intervals etc. but also the biological processes. In addition, it must be ensured that all necessary measured variables are recorded (such as the switching states of motors, power consumption and revolutions per minute, but also process parameters such as pH values, temperatures, gas production rates, gas composition etc.), and that the corresponding switching of actuators such as valves, agitator motors and pump motors is triggered. For acquisition of the measured variables, the values recorded at the sensor are transduced into standard signals that can be utilised by the PLC.

Actuators are switched via relays. The activation signals can simply be time-controlled or they can be defined as a response to incoming measured variables. A combination of these activation options is also possible. In terms of instrumentation and control, standard PID (proportional-integral-derivative) controllers and in some cases simple fuzzy-logic controllers are implemented in all PLC types. Other control algorithms can also be implemented manually, though, by dedicated programming.

A PLC comprises a central module (CPU: central processing unit) that contains a microcontroller as its core component. These controllers vary in their performance, depending on the category of PLC. The differences lie in the processing speed and the redundancy of functions. The range extends from relatively small CPUs, which are correspondingly cheaper to buy, to high-availability systems with high-end controllers and corresponding redundancy.

When it comes to choosing a PLC, real-time barriers are an important factor. Real time in this connection means that the automation system has to respond within a period of time dictated by the process. If this is the case, the automation system has real-time capability. As the biogas process does not have particularly high real-time requirements, PLCs in the low to medium price sector are usually favoured in biogas plants.

In addition to the CPU, a large number of modules are offered by all manufacturers for interfacing with the CPU. These modules include analogue and digital modules for input from signal transmitters and measuring probes and for output to various actuators and analogue indicating instruments. Special connections for measuring instruments controlled via RS-232 interfaces can be of interest for the biogas sector.

Various communication controllers are available for bus communication.

5.2.1 Bus system

In recent years distributed configurations have become more and more widespread in the automation sector, a trend made possible by powerful communication technology. Bus systems are indispensable for distributed plant control nowadays; they carry communication between individual bus users. Bus systems enable all plant components to be networked with each other.

As in the case of PLCs, bus types of various designs are available. Which form of bus communication is appropriate depends on the process and its real-time requirements, and on the specifics of the environment (for example a potentially explosive atmosphere). PROFIBUS-DP is an established standard used in many plants. It enables stations to be linked over distances of several kilometres. Many devices support this standard of bus communication, and the evolved forms PROFINET and ETHERNET are also becoming increasingly common.

5.2.2 Configuration planning

Another component of a PLC is the program on which the process control system is founded. This program is developed in the configuration planning phase in a dedicated development environment, the configuration planning software, and implemented on the PLC. Depending on the requirements for the PLC, this process control program may contain anything from simple open-loop control jobs to complicated feedback control mechanisms. Automatic and manual modes can be configured to permit manual intervention.

It must be possible to operate the plant manually in case plant states arise that are not envisaged in the control system's program. This may be the case in extreme process states or in the event of breakdowns such as pump failures, for example. Provision must be made for automatic shutdown of the plant in the event of major breakdowns or accidents. In such cases the entire plant, or the part of the plant affected, is put into a safe operating state by the triggering of certain sensors or an emergency stop button. Similarly, precautionary measures have to be taken if the supply voltage to the control system itself fails. To cater for this eventuality, controller manufacturers offer uninterruptible power supplies (UPSs) to sustain the power supply to the controller. This enables the controller to perform a controlled shutdown of the plant, thus ensuring that the plant does not enter an undefined state.

5.2.3 Applications/visualisation

PCs and panel variants with appropriate visualisation are another constituent of modern automation solutions. They are interconnected by a bus system, and taken together they form the automation system. Visualisations are used in almost all plants and constitute the state of the art. It is common to find panels that are available in various versions and are used to display a small subsection of a plant.

It is conceivable, for example, to use a panel solution for local visualisation of the substrate feed pump. In automatic mode, all important data (such as motor speed, motor temperature, delivery rate, faults, etc.) are displayed locally. After changeover to manual operation, the pump can be controlled manually. The development of panel technology is ongoing, and already complex visualisation tasks up to and including control tasks can be handled using panels.

The 'classic' visualisation solution is PC-based visualisation. This ranges from the display of individual subprocesses to sophisticated instrumentation and control centres. An I&C centre is a facility where all the information comes together in one place and the process or plant is controlled by human decisions.

In order to enable access to the PLC data using PC applications, a standard was introduced that governs communication between Windows applications and the PLC. The OPC server is a standardised communication platform that can be used to set up non-proprietary communication links. It allows a flexible network to be set up between different types of control system and other applications without the individual stations needing precise information about their partners' interfaces and without the application requiring information about the control system's communication network. This makes it possible to use non-proprietary applications such as data acquisition software or a specially adapted visualisation setup.

5.2.4 Data acquisition

In order to ensure reliable data acquisition in large-scale technical applications, it is common to use databases. The PLC manufacturers offer their own data acquisition systems, but preference should be given to non-proprietary solutions because they are more flexible with regard to access options.

The data that need to be stored can be selected from the multiplicity of data collected. This enables plant operation to be evaluated over a longer period of time. It is also possible to store events, such as fault messages.

A detailed description of the monitoring and control of purely technical matters such as fill levels, pump ON times etc. is not required in the context of this document. The coordination and control of these processes are state of the art and are usually unproblematic.

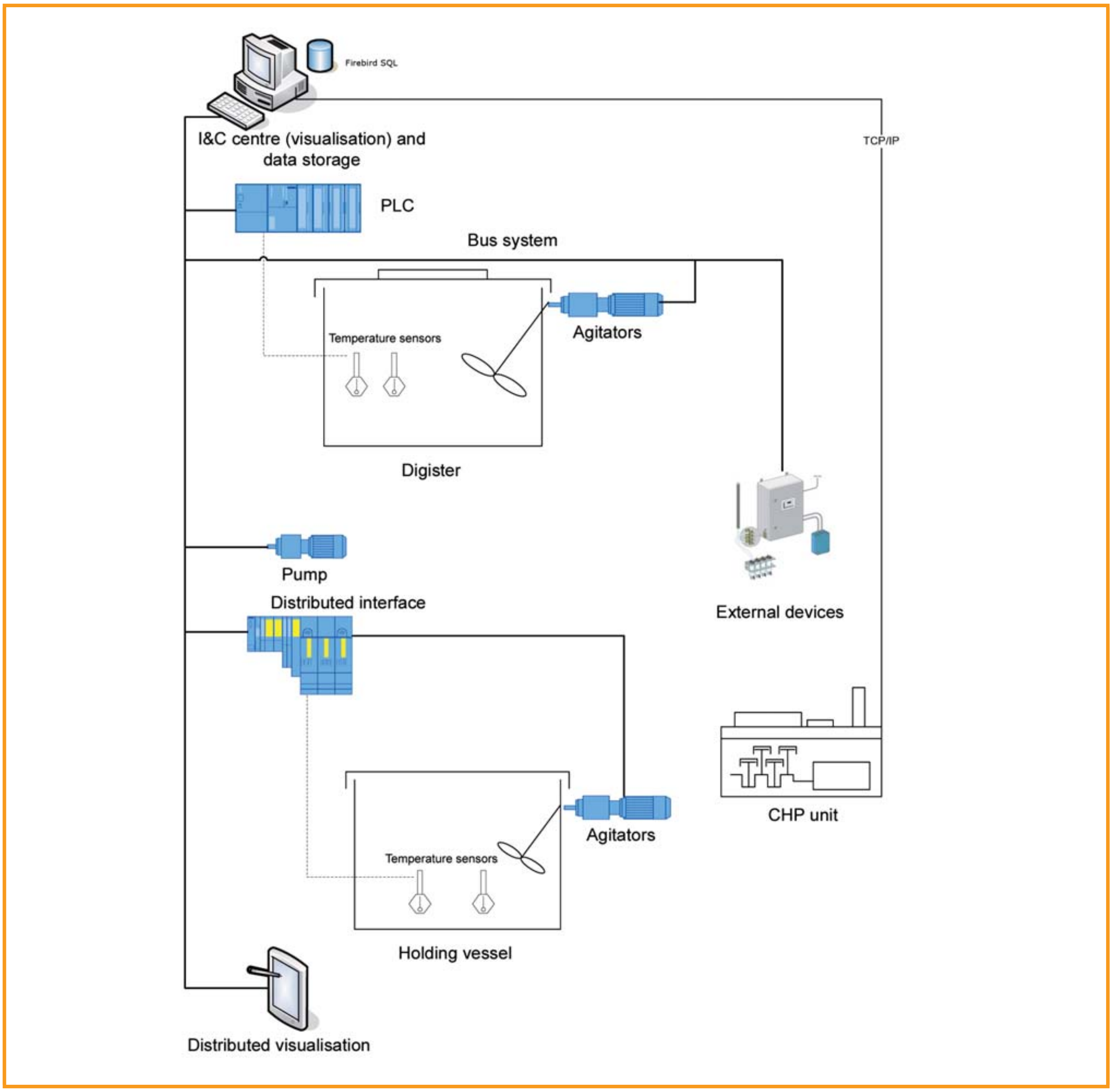

Figure 5.2: Schematic representation of plant monitoring

5.2.5 Feedback process control

The purpose of feedback process control is to ensure achievement of the process objective. The controller detects deviations from the desired state by evaluating measured data, and initiates the measures needed to return the plant to the desired state.

In contrast with open-loop control, in a feedback control system the process reaction is incorporated into the control operation. Exclusively open-loop control systems are unsuitable for the anaerobic degradation process because in the event of unforeseen disturbances the control mechanism does not register the changes in the process and therefore is unable to initiate an appropriate response. Every type of process control – even when undertaken by the operator – requires prior measurements which make it possible to describe the process state to an adequate degree of accuracy, otherwise process disturbances are not detected in good time and serious loss of performance can ensue when disruptions do occur.

In practical circumstances in biogas plants, process control in relation to the biological process is generally undertaken by the plant operator. The operator compares the available measured values with empirical values and performance targets in order to arrive

Table 5.5: Methods of feedback control

Control methods	Application	Comments
PID (proportional-integral-derivative) controller	If little data is available, no model is available and little is known about the behaviour of the controlled system	Good results, limited to simple input/output strategies and linear behaviour
Physical, process-oriented models	Knowledge of internal process flows required	Precise determination of parameters required, for which measured data are essential; suitable for non-linear behaviour
Neural networks	If no simulation model is available; no understanding of the process needed, large quantities of data required	Very good results, but caution required with the type of learning, the controller remains a black box
Fuzzy logic	Small amounts of data required, expert knowledge needed if no simulation model is available	Can be used if there are non-linearities in the process and in multiple input/output scenarios, expert knowledge can be integrated, simple handling

at an assessment of the process state. The efficacy of this approach is heavily dependent on the availability and knowledge level of the operating personnel.

If it is planned to set up an automated process monitoring and control system, the demands on measured value acquisition and evaluation are greater, because the plant operator is not available as a decision-maker and therefore only the process information that is available in electronic form can be used for controlling the plant.

Automatic control systems for biology are not the state of the art in large-scale technical applications. As the industrialisation of plant operation increases, however, and given the aim of raising efficiency, they will be put to greater use in future. Some of the options are presented below, without going into very great detail, for which reference should be made to the relevant specialist literature.

5.2.5.1 Standard methods of feedback control

Various methods have already proved suitable for controlling the process of anaerobic digestion. The problematic aspects of process control are the non-linear nature of the process and the complexity of the processes involved.

PID controller

The principle behind a proportional-integral-derivative (PID) controller is the most widely used algorithm in industrial applications of feedback control. It combines three control mechanisms. The proportional element represents the factor that determines the amplitude of the change in the manipulated variable. The manipulated variable is changed in proportion to the deviation of the process from the desired state. The factor used for this is the proportionality factor. An integral component can be added to this proportional controller. This component is necessary if a deviation occurs when there is a lasting change in the system and the deviation cannot be compensated by the proportionality factor. This problem was solved with the aid of an element that is proportional to the integral of the deviation. The derivative element is proportional to the increase in the deviation, and allows a quick response to be made to large deviations.

$$u = u_0 + k_p e + k_i \int e dt + k_d \frac{de}{dt}$$

Equation 5.4: PID controller (u controller output, u_0 basic output of controller, e process deviation, k_p proportionality factor, k_i factor of integral element, k_d factor of derivative element)

A PID controller exhibits linear, non-dynamic behaviour. It is not possible to map correlations between different measured variables.

PID controllers are widely used and are also suitable for many applications in biogas plants. They can be used for correcting the oxygen content in the biogas necessary for desulphurisation, for example, or for controlling the temperature in the digester. In certain circumstances this simple algorithm can also be used for controlling the biogas process [5-35], [5-37].

In principle, feedback control systems can be implemented with any of the methods described above; this has been proved on the laboratory scale. Control systems that have been developed on the basis of physical, process-oriented models, knowledge-based systems or neural networks, however, have rarely been used in practical operation to date.

5.2.5.2 Other approaches

Many plant manufacturers also offer advisory services and analysis services packages to support operation, targeted at optimising the biological process. Such services are also offered by independent companies that perform consultancy work and offer emergency assistance. Another option offered is direct process analysis on the basis of process dynamics ('communication with the process'). In this case the performance of the process is evaluated on the basis of the dynamic response by the process to an introduced 'fault'.

There are also various forums on the internet where operators swap experiences about problems they encounter. In addition, some organisations offer training courses for plant operators and personnel.

5.3 Process control in start-up and standard operation

5.3.1 Standard operation

In the following a brief explanation is given of which process parameters should be polled so that process biology can be assessed. A distinction is drawn between two different plant scenarios, because the outlay involved depends on the type of plant and the mode of operation. As far as acquisition of the data is concerned, it is initially irrelevant whether this is done online or manually. What is important is that the data is pre-processed for appropriate analysis.

Scenario 1: normal plant, slurry-based, low organic loading rate (less than 2 kg $VS/m^3 \cdot d$), no inhibitory substances, concentrations of acids in normal operation less than 2 g/l.

Scenario 2: plants with high organic loading rate, varying composition and quality of the substrate, possibly inhibitory substances (e.g. ammonium above 3 g/l), concentrations of acids in normal operation above 2 g/l, and when changes are made to the loading regime.

Table 5.6: Measuring program for biogas plants for monitoring the biological process (normal operation)

Quantities required for process evaluation	Unit	Plant scenario 1	Plant scenario 2
Input quantity	m^3	daily	daily
Input composition	kg DM/m^3 ; kg VS/m^3	monthly	weekly
Temperature	°C	daily	daily
Intermediate products (organic acids)	g/l	monthly	weekly
Output quantity	m^3	daily	daily
Composition of fermentation residue	kg DM/m^3 ; kg VS/m^3	monthly	weekly
Quantity of gas generated	m^3	daily	daily
Composition of biogas	Vol. % methane, carbon dioxide, hydrogen sulphide, optionally oxygen	daily	daily
pH value	-lg H_30^+	monthly	weekly
Additional measurements			
Ammonium concentration, total nitrogen	g/l g/kg	monthly	weekly
Trace elements	g/l	as required	as required
Specific gas production	l/kg VS	monthly	weekly
Organic loading rate	kg $VS/m^3 \cdot d$	monthly	weekly
Dwell time	d	monthly	weekly
Specific gas production rate	$m^3/m^3 \cdot d$	monthly	weekly

Plants experiencing disturbances, i.e. with changing process parameters, should be sampled with a measuring density at least that shown in scenario 2. Dynamic process states always involve the risk of process excursions outside the range within which self-stabilisation is possible. Consequently, changeovers of the operating regime, substrate changes, increases in input quantities etc. should always be accompanied by a significantly higher measuring density.

If it is known that the process is exposed to potentially inhibitory substances (e.g. ammonia) because of the nature of the operating conditions, it makes sense to observe these substances as well. This will enable the cause of disturbances to be identified more quickly.

If balancing of the process leads to a reduction in degradation performance, the next step must be to analyse the cause. The causes of disruptions and disturbances, and how to correct them, are discussed in Section 5.4.1. The data should be acquired or pre-processed electronically, because this makes long-term trends and correlations easier to identify.

In most plants, process evaluation is based on the experience of the plant operator. Evaluation can be performed with greater precision and more objectively with the aid of a process monitor. Process monitors evaluate the data on the basis of mathematical models. Especially when dynamic changes occur in the process, such as substrate changes or changes to the feed volume, it is not possible to evaluate the process transient without a model. The same applies to forecasting process behaviour in order to calculate future feed volumes.

Building on process evaluation, only model-based control systems are capable of producing forecasts of process trends. If the measured values are not integrated into a model, they are at best suitable for a static snapshot and therefore not suitable for dynamic control.

As a general rule in plant operation, the feeding regime should only be changed – if at all – in such a way that the effects can be understood. This means that only one parameter should be adjusted at a time, and all the others kept constant. If not, the effects can no longer be assigned to the causes, and process optimisation becomes impossible.

In normal operation, mono-fermentation should be avoided and preference should be given to using a substrate composition that is diverse but remains as constant as possible over time. For the purposes of optimisation, it makes sense to change the mixture proportions in such a way as to obtain an optimum ratio between organic loading rate and dwell time.

The biological process is most effective under constant conditions. Setting constant feed volumes and a consistent substrate composition with a high degree of accuracy is therefore an important step toward process optimisation.

5.3.2 Start-up process

Start-up processes differ from normal operation in that the system has not yet reached the steady state. The processes taking place are subject to constant changes to the process parameters. In order to be able to run the process safely at full load in this state, a greater measuring density is required than in normal operation because the process is unstable and is liable to collapse much more quickly.

During start-up the digesters must be loaded within as short a time as possible until all inlets and outlets (liquid seals) are sealed off with liquid. During start-up operation, particular attention must be paid to the fact that explosive gas mixtures may form in the gas space of the digester. Loading must therefore proceed swiftly. If insufficient seed material (inoculum) is available for start-up operation, the seed material should be diluted with water in order to reduce the size of the gas space. The agitators must be submerged when in operation during the start-up phase in order to prevent sparking.

After filling, the contents of the tank must be set to a constant temperature, after which loading of the substrate can begin.

When the plant is started up for the first time, the start-up phase can be shortened by adding a sufficient quantity of bacteria involved in the degradation process as seed material. The greater the amount of seed material added, the shorter the running-in phase. In an ideal situation, therefore, the digester being started up would be completely filled with fermentation residue from another plant. Depending on availability, it is also possible to use a mixture of fermentation residues from various plants, plus slurry and water. When water is added it should be remembered that the system's original buffer capacity is reduced as dilution increases. Consequently, if the loading rate is increased too quickly the process can easily become unstable, thereby significantly increasing the risk of process collapse in the digester.

The use of slurry always has a positive impact on the start-up process. This is because slurry generally contains a large amount of trace elements as well as a multitude of different bacterial populations. Cattle slurry, in particular, contains enough methanogenic archaea for the process to become stabilised quickly on its own. Pig slurry, on the other hand, is not as rich in methanogenic microorganisms, but is usable in principle.

After a steady temperature is reached, it is best to wait until pH stabilises in the neutral range, the methane content in the generated biogas is greater than 50% and the concentration of short-chain fatty acids is below 2,000 mg/l. Loading can then begin. Loading should be successively increased, in stages, until full load is reached. After each increase it is best to wait until the relevant process parameters, namely gas production rate, methane content, VOA/TAC value or acid concentration and pH value, have stabilised, at which point a further increase in the organic loading rate can be initiated. The VOA/TAC value is of only limited significance, but for start-up operation it is suitable for use as a monitoring parameter for assessing process stability as it can be registered very easily and cost-effectively at high density. In order to obtain reliable information about process stability, the acid spectrum should also be analysed in addition from time to time, to identify the type of acids present.

Normally an increase in the loading rate is followed by a short-term rise in the VOA/TAC value. In certain circumstances, gas production even decreases slightly. The clarity of this effect varies, depending on the level of the increase. If the loading rate then remains the same, the VOA/TAC value should stabilise again and gas production should settle down at a level appropriate to the input. Only then should the loading rate be increased further. If gas production falls for a certain period of time while loading remains constant, and the VOA/TAC value is higher, a process disturbance has already occurred. In this case loading should not be further increased, and if appropriate the input volume should even be reduced, depending on how the VOA/TAC value develops.

To sum up it can be stated that the following factors have a clearly positive impact on start-up operation:

- Use of fresh cattle slurry or active seeding sludge from biogas plants that are operating well
- A finely tuned, dense measuring program for the biological parameters (see Tab. 5.6)
- Continuity in substrate feeding and substrate quality
- Trouble-free plant operation.

Even when full loading is achieved, this does not mean that a steady state is established. This state is reached only after a period corresponding to roughly three times the dwell time.

Special measures need to be taken if high concentrations of ammonia are anticipated. In that case the process may need lengthy adaptation phases, lasting several months or up to a year. This can be a highly significant factor, for example when planning the financing of the plant. In such cases it is always advisable to use fermentation residue from a plant already using similar substrate. Consideration should be given to establishing the target final concentration of ammonium as quickly as possible so that the bacteria can adapt to the final state immediately, because otherwise another adaptation will be needed each time the concentration is raised. The final concentration can be reached quickly by loading the intended final-state substrate mixture from the very beginning.

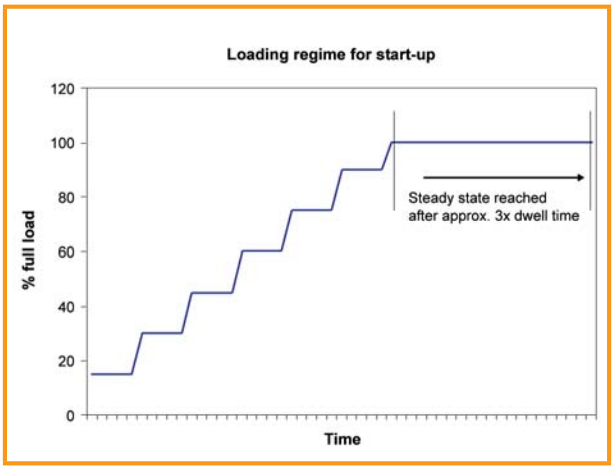

Figure 5.3: Loading regime for start-up

In plants that are run entirely on energy crops and are started up with slurry, trace-element paucities tend not to appear for about 6 to 12 months. These plants in particular, therefore, must be carefully observed even after successful start-up of the process.

Whatever the case, then, more process monitoring is necessary during the first year of operation.

It is advisable to use fully fermented material from existing plants for the start-up process in dry fermentation plants with garage-type digesters that will be operated on energy crops or landscape management material. Slurry is not suitable for starting dry fermentation because it can cause blockages in the percolate nozzles of the batch-type digesters on account of the suspended solid matter. Instead, the process should be started with clear water as the percolation liquid and with filled batch-type digesters, preferably filled with fully fermented material.

Start-up operation for a biogas plant with three digesters, each with a working volume of 4,000 m³, is described in the following, by way of example. Different start-up strategies, each leading to normal plant operation, are elucidated.

Digester 1	Mixture of digestate from two plants (each 20%), cattle slurry (10%), water (50%), total solids content approx. 1.5% FM, filling and stabilisation of temperature took about 25 days
Digester 2	Mixture of digestates from 3 different plants (approx. 44%), cattle slurry (6%), digestate from digester 1 (50%)
Digester 3	Filled completely with digestate from digesters 1 and 2

Digester 1: After the operating temperature of 37 °C was reached, initial dosing of solid matter was begun. Only maize silage was used as the substrate.

In the start-up strategy chosen in this example, first of all relatively large amounts of substrate were added in batches, with waiting times between the batches depending on the level of gas production. Comparatively high organic loading rates were chosen from the outset, and the time between the substrate surges was increasingly shortened. The advantage of this start-up strategy is that, as a rule, full-load operation can be achieved more quickly than with continuous increases in small steps. The parameters for deciding when to further increase loading were the development of the VOA/TAC quotient with simultaneous observation of the development of the concentrations of fatty acids and of gas production from the digester.

The organic loading rate and the VOA/TAC value during start-up operation in digester 1 are graphed in Figure 5.4. It is clear that the surge increases in loading led to considerable process disturbances. A doubling of the VOA/TAC values can be seen even after the first, relatively small load surges. The reason for the sharp fluctuations is the very high proportion of water in the system and the associated low buffer capacity. The latter leads to the observation that the pH value reacts very quickly to every addition of substrate. Normally the pH value is an extremely slow-reacting parameter; almost no changes to it are detectable in practical operation. Because of the instabilities that occurred, the start-up strategy was changed to the continuous addition of substrate from day 32 onward. Thanks to a slow but steady rise in input quantities it proved possible to increase the organic loading rate to an average of 2.6 kg VS/(m³ · d) by day 110. The start-up strategy of surge loading can lead to full-load operation being reached more quickly under the right conditions, such as high seeding sludge activity and intensive process monitoring. In the example shown here, this strategy proved inappropriate because of the low buffer capacity resulting from the high water content.

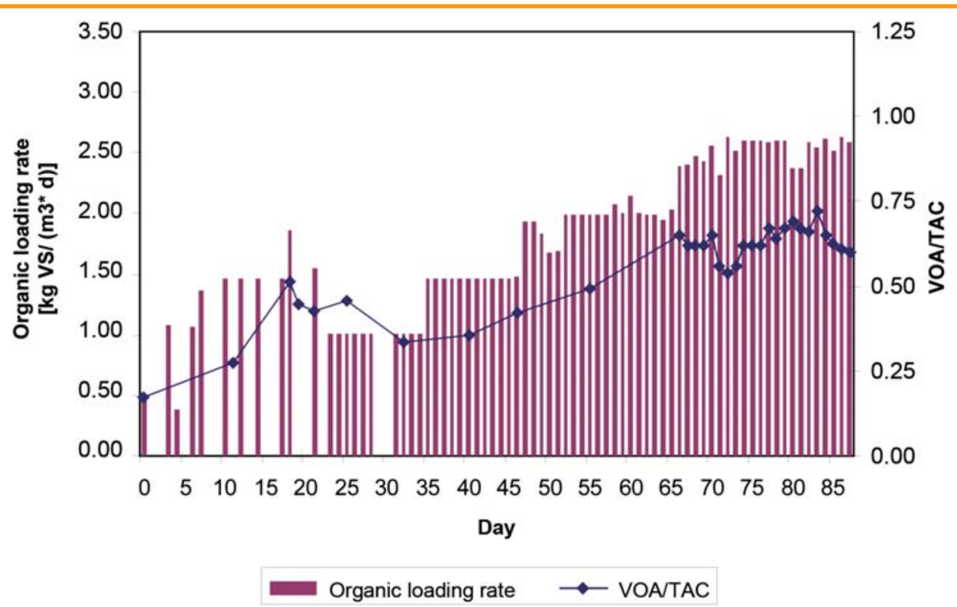

Figure 5.4: Progress of start-up phase, digester 1

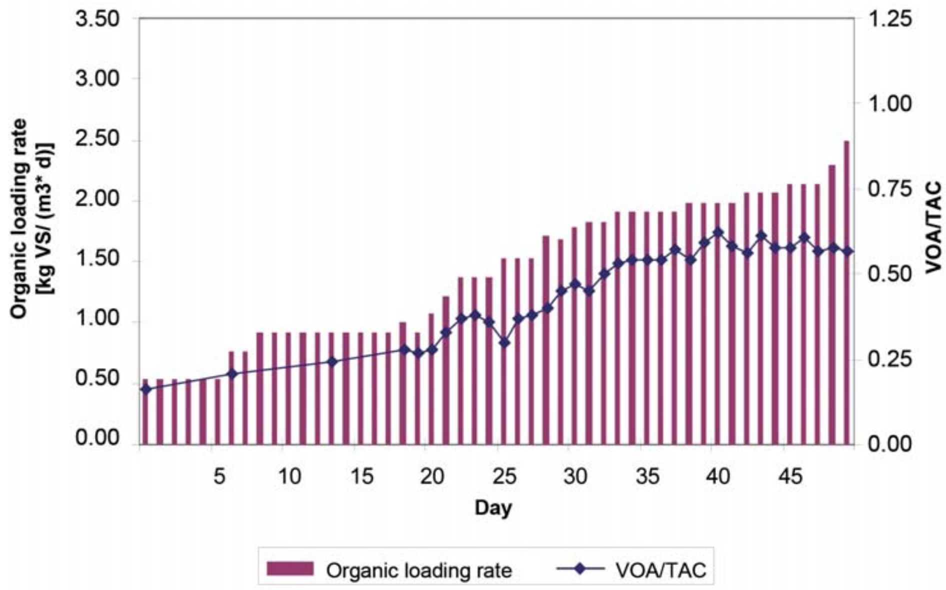

Figure 5.5: Progress of start-up phase, digester 2

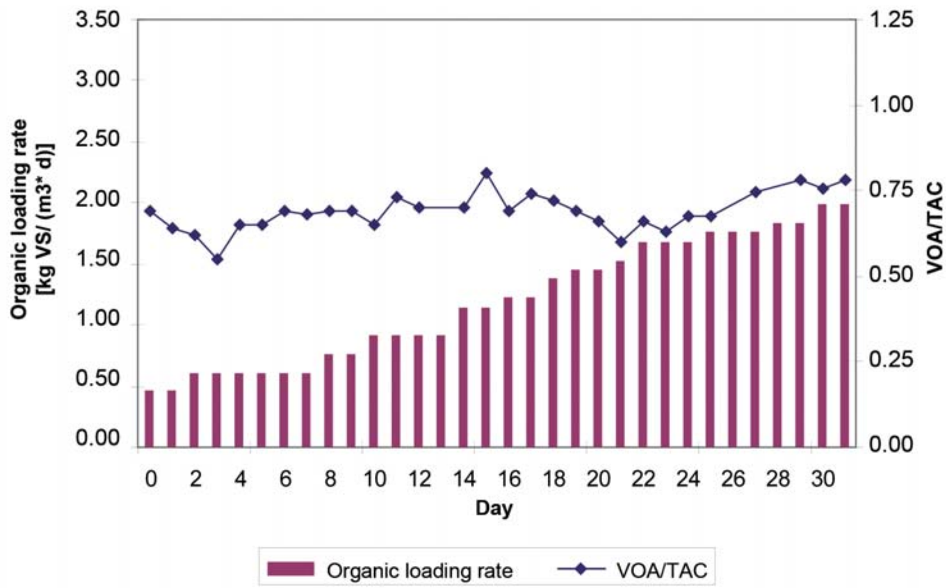

Figure 5.6: Progress of start-up phase, digester 3

Digester 2 was filled concurrently with start-up operation of the first digester.

Start-up operation of digester 2 is shown in Figure 5.5. By day 50 the organic loading rate was up to about 2.1 kg VS/($m^3 \cdot d$), with an upward trend in VOA/TAC values. Despite the rising VOA/TAC value, it proved possible to run the digester up to full load quickly and in a controlled manner.

A graph illustrating start-up operation of digester 3 is shown in Figure 5.6. In this case it proved possible to increase the organic loading rate to 2.1 kg VS/($m^3 \cdot d$) within 30 days, with constant VOA/TAC values. Using fermentation residue for the first filling allows a rapid run-up to full load. The higher VOA/TAC values were already present in the fermentation residue.

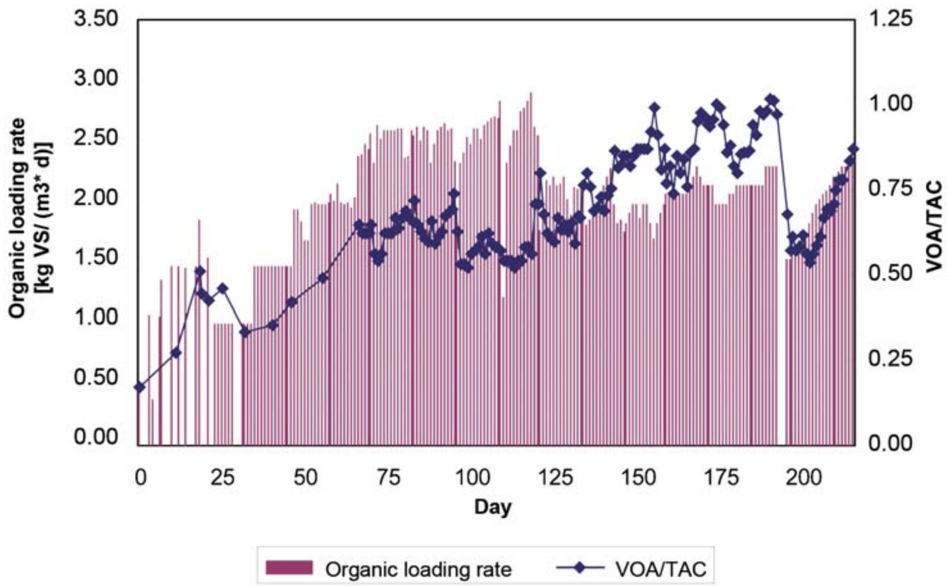

Figure 5.7: Progress of start-up phase of digester 1 with a deficiency of trace elements

The different first loads have significant impacts on process stability and the rate of rise to full load. It is apparent that the higher the proportion of fermentation residue and the better the microorganisms are adapted to the substrate properties, the quicker the digester can be started up and the more stable this process will be.

In the following, a description is also given of a typical course of events leading to inhibition due to a deficiency of trace elements. After successful start-up, the plant was operated in a stable condition between day 60 and day 120. As operation continues, however, the seed material (fermentation residues and slurry) is leached out and concentrations are established matching those of the substrate (maize silage). In this case the substrate does not contain enough trace elements. This leads to a deficiency, which manifests itself in the inhibition of methanogenesis. As a consequence of this inhibition, the acids that are formed can no longer be degraded, and the VOA/TAC values rise during stable operation after about 120 days of operation and subsequently, despite a reduction in organic loading rate (see Figure 5.7). The causes and possible countermeasures are described in more detail in Section 5.4.2. If no intervention is made during this phase, process collapse in the digester is inevitable. It should be pointed out once again that the particular feature of this process disturbance is that it does not occur until several months into operation, depending on the seed material and the way the system is managed.

5.4 Disturbance management

5.4.1 Causes of process disturbances

The term process disturbance refers to occurrences when anaerobic digestion in the biogas plant is negatively affected and is therefore not proceeding at its optimum. The result is that the substrates are insufficiently decomposed. Process disturbances, whatever their extent, therefore always have a detrimental effect on the economic efficiency of the biogas plant. Consequently, process disturbances must be detected and corrected as quickly as possible.

Process disturbances occur when the environmental conditions for the bacteria or individual groups of bacteria are less than optimal. The speed at which the process disturbance appears varies, depending on how strong the influence is and the period of time within which the conditions have changed for the worse. In most cases process disturbances are indicated by a continuous rise in the concentrations of fatty acids. This occurs regardless of the cause, which is due to the fact that the acetogenic and methanogenic bacteria respond more sensitively to changes in their environment than the other bacterial groups. Without intervention, the typical course of a process disturbance is as follows:

- Rise in fatty acid concentrations:
  initially acetic and propionic acid, and if process loading persists also i-butyric acid and i-valeric acid

- Continuous rise in the VOA/TAC ratio (in parallel with the rise in fatty acids)
- Reduction in methane content
- Reduction in gas yield despite constant feeding
- Lowering of the pH value, acidification of the process
- Complete collapse of gas production.

Possible causes of process disturbances, such as deficiencies (trace elements), fluctuations in temperature, inhibitory substances (ammonia, disinfectants, hydrogen sulphide), errors in feeding, or overloading of the process, are described in the following. For plant operation to be successful it is very important to detect process disturbances at the earliest possible stage (cf. Section 5.1). This is the only way of identifying and eliminating the causes in good time, thus minimising the economic damage.

The problems relating to trace element deficiency and ammonia inhibition were discussed in Sections 5.1.8 and 5.1.9.

In the operation of biogas plants in practice there can be a variety of causes for a drop in process temperature. Heating the digester is of crucial importance in moderate temperatures such as those encountered in Germany, and if the heating fails the fermentation temperature can drop several degrees relatively quickly. In such cases it need not necessarily be the heating system itself that is faulty, as illustrated by the following scenario.

If the CHP unit stops running, after a certain time the necessary waste heat for heating the digester is no longer available. The drop in temperature inhibits the activity of the methanogenic bacteria, as they only survive within a narrow temperature window [5-1]. The bacteria involved in hydrolysis and acidogenesis are less specialised in this respect and are initially able to survive a drop in temperature. The consequence, however, is that the acids in the digester become more concentrated, especially if the substrate feed is not slowed down or stopped in good time.

In such an event, in addition to the temperature inhibition there is also a drop in pH value, with acidification of the entire contents of the digester.

However, the addition of large quantities of unpreheated substrate, or inadequate heating of the digester as a result of failure of the temperature sensors, for example, can also lead to a drop in digester temperature. It is not the absolute temperature that is crucial for a stable process but the maintenance of a constant temperature level. If a change in temperature (up or down) takes place within a short period of time, an adverse effect on degradation can generally be expected to result. It is therefore hugely important to check the fermentation temperature regularly to ensure successful operation of the plant.

As already explained in Section 5.1.3, the process temperature may rise when certain substrates are used. The temperature then moves from the mesophilic range to the thermophilic range, without the need for expending additional heating energy. If plant operation is not managed properly, in the worst case the process can come to a complete standstill on transition from the mesophilic to the thermophilic temperature range.

The operating conditions of a biogas plant must be kept as constant as possible. This applies to the environmental conditions in the reactor just as much as to the nature and metering of the substrates. Mistakes are made in the addition of substrate in the following circumstances:

- too much substrate is added over a long period of time
- substrate is added too irregularly
- a rapid change is made between substrates of differing composition
- too much substrate is added after a break in feeding (e.g. because of technical faults).

Most mistakes relating to the addition of substrate are made during start-up operation and when changing substrate during normal operation. This is why the process needs to be kept under particularly close observation in these phases. It is also advisable to intensify in-process analysis. With some substrates there are also considerable variations in composition from one batch to the next, which results in undesirable fluctuations in organic loading rate.

5.4.2 Handling process disturbances

As previously mentioned, a process disturbance can be lastingly corrected only if the cause has been identified and eliminated. That said, there are some control engineering measures that can be taken to relieve the situation, at least temporarily. The following sections firstly describe fundamental measures aimed at process stabilisation and the effects that they have. The success of these measures generally depends on the degree of disturbance affecting the process, i.e. the extent to which the microorganisms have already been adversely affected. Furthermore, the process must be kept under very close observation while the measures are being implemented and during the subsequent recovery phase. Success or failure of the action can thus be recognised quickly, and further steps initiated as necessary. Possible ways of eliminating the process disturbances are then described, to match the causes pointed out in the preceding section.

5.4.2.1 Measures aimed at stabilising the process

Reduction in input volume

Reducing the input volume (while maintaining the same substrate composition) lowers the organic loading rate. This effectively relieves the strain on the process. Depending on the extent to which the addition of substrate is reduced, the methane content of the biogas subsequently rises noticeably. This is an indication of the degradation of the fatty acids that have accumulated up to that point, although acetic acid is degraded very quickly and propionic acid very slowly. If the concentrations of propionic acid are excessively high, it is possible that this substance will no longer be broken down. In that case other steps have to be taken to relieve the strain on the process.

If gas production remains constant after input volume has been reduced, this is an indication of the digester being significantly overfed. The fatty acid concentrations should be checked and a noticeable reduction in gas production observed before the input volumes are slightly increased again.

Material recirculation

Recirculation means returning material to the digester from a downstream receptacle (e.g. secondary digester or digestate storage tank). The benefits of recirculation, if it is feasible in process engineering terms, are essentially twofold. Firstly a dilution takes place, which means that the 'pollutant concentration' in the digester is reduced, depending on how long recirculation is sustained. Furthermore, 'starved' bacteria are returned to the digester, and are again able to play an effective part in degradation.

This approach is primarily recommended for multi-stage plants. In single-stage plants this method should be used only if gas-tight digestate tanks are available, and even then only in emergencies. In a system involving material recirculation, attention must be paid to the temperature of the recirculated material and if necessary a constant temperature must be ensured in the digester through the provision of additional heating.

Changing the input composition

Changing the input composition can stabilise the process in various ways. Firstly, changing the mixture can reduce the organic loading rate by replacing/omitting energy-rich constituents (e.g. cereal grains), thereby relieving the strain. Secondly, supplementing the input composition by adding liquid or solid manure (e.g. cattle slurry), if this is not otherwise used, can have a significantly positive impact through the provision of additional trace elements and other bacterial groups. The addition of fermentation substrate from another biogas plant can have an equally positive effect. With regard to the mono-fermentation of energy crops, it should be noted that the addition of another substrate component normally has a positive impact on process stability.

5.4.2.2 Deficiency of trace elements

As a rule, a paucity of trace elements can be compensated for by adding manure (cattle or pig slurry or cattle or pig dung). If these substrates are not available to the plant operator in sufficient quantities or cannot be used for some other reason, there are various suppliers of trace element additives on the market. On the whole, these are complex mixtures. However, as trace elements are heavy metals, which can have an inhibitory effect on the process if added in excessive quantities [5-16] and which also accumulate on agricultural land, trace element loads must be kept to a minimum [5-17]. If possible, only those trace elements that are actually deficient should be added. In such cases an analysis of the trace elements in the digester material and the input materials can provide useful information. That said, an analysis of this type is complex and costly.

In order to increase the efficiency of adding trace elements, iron salts can be added to the process for the purposes of chemical desulphurisation before the trace element mixture (cf. Section 2.2.4). In this way a large proportion of the dissolved hydrogen sulphide can be precipitated out and the bioavailability of the trace elements will be improved. It is invariably important to pay attention to the manufacturer's recommendations and follow the instructions.

5.4.2.3 Response to temperature inhibitions

If the process is subject to temperature inhibition as a result of self-heating, there are two possible ways of addressing the problem. Either the process can be cooled, or the process temperature can be changed. In some cases cooling can be brought about by technical means using the heating system, but usually this is difficult to achieve. Adding cold water can also produce a cooling effect, although likewise this must also be done extremely carefully. If the aim is to change the process temperature from the mesophilic to the thermophilic range, targeted biological support is required in the transition period. The microorganisms first have to adapt to the higher temperature level, or new microorganisms have to be formed. During this period the process is extremely unstable and must under no circumstances be allowed to 'collapse' through the addition of too much substrate.

5.4.2.4 Response to ammonia inhibition

Action aimed at reducing ammonia inhibition requires fundamental intervention in the operation of the plant. As a rule, ammonia inhibitions occur when protein-rich input materials are used. If ammonia inhibition has been demonstrably verified, either the temperature must be lowered or the input composition changed. Changing the input composition should result in a reduction in nitrogen load. This can bring about a long-term reduction of the concentration of inhibiting ammonia in the digester. If acidification is already far advanced, it makes sense to swap fermentation residue from a downstream digester in order to reduce acid concentration in the short term.

Whichever method is chosen, it should be done slowly, with close monitoring of the process. Lowering the pH value in order to reduce the proportion of undissociated ammonia is extremely difficult to achieve in the long term and therefore cannot be recommended.

5.4.2.5 Response to hydrogen sulphide inhibition

The occurrence of hydrogen sulphide inhibition is extremely rare in agricultural biogas plants. Hydrogen sulphide inhibition is always related to the substrate, i.e. attributable to a high sulphur content in the input materials. For the most part, the input materials used in agricultural biogas plants have a relatively low sulphur content. That said, the H_2S content in the gas must always be kept low because of its negative repercussions for gas utilisation. The following steps can be taken to counter hydrogen sulphide inhibition:
- Add iron salts for sulphide precipitation
- Reduce the proportion of input materials containing sulphur
- Dilute with water.

Raising the pH value with the aid of buffer substances can reduce the toxicity of the H_2S for short periods but should not be relied upon for the long term.

5.4.3 Handling technical faults and problems

Given the considerable differences in design and technical equipment between agricultural biogas plants it is impossible to give general recommendations in this document on how to remedy technical faults. However, reference should always be made to the biogas plant's operating instructions, which normally contain recommendations for action and steps to be taken to eliminate problems with individual plant components.

With all technical faults and problems, it is crucially important that they are detected and eliminated in good time. An automated alerting system is essential for this. The operational status of the key plant components is recorded and monitored in the process management system. If a technical fault occurs, an alert is issued in the system and can be forwarded to the plant operator or other operating personnel by telephone or text message. This procedure enables remedial action to be taken swiftly. In order to avoid lengthy disruption to operation, it is important that the plant operator always stocks a selection of spare parts and wear parts. Downtimes and repair times can thus be reduced. In addition, in case of emergency the plant operator should if possible be able to call on a reliable service team at any time. Usually the plant manufacturer or external specialist workshops offer such services directly. To minimise the risk of technical faults, the plant operator must ensure that regular checks are performed and that the maintenance intervals are observed.

5.5 Operational reliability

5.5.1 Occupational safety and plant safety

Biogas is a gas mixture consisting of methane (50-75 vol. %), carbon dioxide (20-50 vol. %), hydrogen sulphide (0.01-0.4 vol. %) and other trace gases [5-1], [5-6]. The properties of biogas are contrasted with other gases in Table 5.7. The properties of the various components of biogas are summarised in Table 5.8.

In certain concentrations, biogas in combination with atmospheric oxygen can form an explosive atmosphere, which is why special plant safety regulations have to be observed in the construction and operation of a biogas plant. There are also other hazards, such as the risk of asphyxiation or poisoning, as well as mechanical dangers (e.g. risk of crushing by drives).

Table 5.7: Properties of gases [5-6]

		Biogas	Natural gas	Propane	Methane	Hydrogen
Calorific value	kWh/m^3	6	10	26	10	3
Density	kg/m^3	1.2	0.7	2.01	0.72	0.09
Density relative to air		0.9	0.54	1.51	0.55	0.07
Ignition temperature	°C	700	650	470	600	585
Explosive range	vol. %	6-22	4.4-15	1.7-10.9	4.4-16.5	4-77

Table 5.8: Properties of biogas components [5-6], [5-7], [5-8]

		CH_4	CO_2	H_2S	CO	H
Density	kg/m^3	0.72	1.98	1.54	1.25	0.09
Density relative to air		0.55	1.53	1.19	0.97	0.07
Ignition temperature	°C	600	-	270	605	585
Explosive range	vol. %	4.4-16.5	-	4.3-45.5	10.9-75.6	4-77
Workplace exposure limit (MAC value)	ppm	n. s.	5000	10	30	n. s.

The employer or biogas plant operator is obliged to identify and evaluate the hazards associated with the biogas plant, and if necessary to take appropriate measures. The 'Sicherheitsregeln für Biogasanlagen' (Safety Rules for Biogas Systems) issued by the Bundesverband der landwirtschaftlichen Berufsgenossenschaften (German Agricultural Occupational Health and Safety Agency) [5-6] provide a concise summary of the key aspects of safety relevant to biogas plants. The safety rules explain and substantiate the safety requirements in terms of the operating procedures relevant to § 1 of the accident prevention regulations 'Arbeitsstätten, bauliche Anlagen und Einrichtungen' (Workplaces, Buildings and Facilities) (VSG 2.1) [5-9] issued by the Agricultural Occupational Health and Safety Agency. They also draw attention to other applicable codes of practice.

This section is intended to provide an overview of the potential hazards during operation of a biogas plant and raise awareness of them accordingly. The latest versions of the respective regulations [5-6], [5-8], [5-9], [5-10] constitute the basis for the hazard assessments and the associated safety-related aspects of plant operation.

5.5.1.1 Fire and explosion hazard

As mentioned in the previous section, under certain conditions biogas in combination with air can form an explosive gas mixture. The explosive ranges of biogas and its individual components are shown in Table 5.7 and Table 5.8 respectively. It should be borne in mind that although there is no risk of explosion above these limits it is still possible for fires to be started by naked flames, sparks from switching electrical equipment or lightning strikes.

During the operation of biogas plants, therefore, it must be expected that potentially explosive gas-air mixtures are liable to form and that there is an increased risk of fire, especially in the immediate vicinity of digesters and gas tanks. Depending on the probability of the presence of an explosive atmosphere, according to BGR 104 – Explosion Protection Rules the various parts of the plant are divided into categories of hazardous areas ('Ex zones') [5-10], within which the relevant signs must be prominently displayed and appropriate precautionary and safety measures taken.

Zone 0

In areas classified as zone 0, an explosive atmosphere is present constantly, over long periods, or most of the time [5-6], [5-10]. Normally, however, no such zones are found in biogas plants. Not even a fermentation tank/digester is classified in this category.

Zone 1

Zone 1 describes areas in which an explosive atmosphere can occasionally form during normal operation. These are areas in the immediate vicinity of manholes accessing the gas storage tank or on the gas-retaining side of the fermentation tank, and in the vicinity of blow-off systems, pressure relief valves or gas flares [5-6]. The safety precautions for zone 1 must be put in place within a radius of 1 m (with natural ventilation) around these areas. This means that only resources and explosion-protected equipment with zone 0 and zone 1 ratings may be used in this area. As a general rule, the operations-related release of biogas in enclosed spaces should be avoided. If it is possible that gas will be released, however, zone 1 is extended to include the entire space [5-6].

Zone 2

In these areas it is not expected that explosive gas-air mixtures will occur under normal circumstances. If this does in fact happen, it can be assumed that it will do so only rarely and not for a lengthy period of time (for example during servicing or in the event of a fault) [5-6], [5-10].

This applies to manholes, for example, and the interior of the digester, and in the case of gas storage tanks the immediate vicinity of aeration and ventilation openings. The measures applicable to zone 2 must be implemented in these areas in a radius of 1 to 3 m [5-10].

In the areas subject to explosion hazard (zones 0-2), steps must be taken to avoid ignition sources in accordance with BGR 104, section E2 [5-10]. Examples of ignition sources include hot surfaces (turbochargers), naked flames or sparks generated by mechanical or electrical means. In addition, such areas must be identified by appropriate warning signs and notices.

5.5.1.2 Danger of poisoning and asphyxiation

The release of biogases is a natural process, as is well known, so it is not exclusively restricted to biogas plants. In animal husbandry, in particular, time and again in the past there have been accidents, some of them fatal, in connection with biogenic gases (for example in slurry pits and fodder silos etc.).

If biogas is present in sufficiently high concentrations, inhalation can produce symptoms of poisoning or asphyxiation, and can even prove fatal. It is particularly the hydrogen sulphide (H_2S) content of non-desulphurised biogas that is highly toxic, even in low concentrations (see Table 5.9).

In addition, especially in enclosed or low-level spaces, asphyxiation can occur as a result of the displacement of oxygen by biogas. Although biogas is lighter than air, with a relative density (D) of roughly 1.2 kg per m^3, it tends to segregate. In this process the heavier carbon dioxide (D = 1.98 kg/m^3) collects close to floor level, while the lighter methane (D = 0.72 kg/m^3) rises.

Table 5.9: Toxic effect of hydrogen sulphide [5-7]

Concentration (in air)	Effect
0.03-0.15 ppm	Perception threshold (odour of rotten eggs)
15-75 ppm	Irritation of the eyes and the respiratory tract, nausea, vomiting, headache, loss of consciousness
150-300 ppm (0.015-0.03%)	Paralysis of the olfactory nerves
> 375 ppm (0.038%)	Death by poisoning (after several hours)
> 750 ppm (0.075%)	Loss of consciousness and death by respiratory arrest within 30-60 min.
above 1000 ppm (0.1%)	Quick death by respiratory paralysis within a few minutes

For these reasons it is essential that adequate ventilation is provided at all times in enclosed spaces, for example enclosed gas storage tanks. Furthermore, personal protective equipment (e.g. gas alarms, respiratory protection etc.) must be worn in potentially hazardous areas (digesters, maintenance shafts, gas storage areas etc.).

5.5.1.3 Maintenance and repair

As a general rule, maintenance of agitation, pumping and flushing equipment should always be performed above ground level [5-6]. If this is not possible, a forced ventilation system must be permanently installed in order to counteract the risk of asphyxiation and poisoning in the event of an escape of gas.

5.5.1.4 Handling of chemicals

A variety of chemicals are used in biogas plants. The most common are various iron salts for chemical desulphurisation, additives for stabilising the pH value, or complex mixtures of trace elements or enzymes for the purposes of process optimisation. The additives come in either liquid or solid (powder) form. As these products generally have toxic and caustic properties, it is important to read the product information before using them and essential to follow the manufacturer's instructions regarding dosing and application (e.g. to wear a dust mask, acid-proof gloves, etc.). As a general rule the use of chemicals should be restricted to the necessary minimum.

5.5.1.5 Other potential accident risks

In addition to the sources of danger described above there are also other potential accident sources, such as the risk of falling from ladders or falling into charging holes (solids metering equipment, feed funnels, maintenance shafts etc.). In these cases it must be ensured that falling into such openings is prevented by covers (hatches, grids etc.) or by installing them at a sufficient height (> 1.8 m) [5-6]. Moving plant parts (agitator shafts, worms etc.) are also potential danger points, which must be clearly identified by appropriate signage.

Fatal electric shocks can occur in and around combined heat and power units as a result of incorrect operation or faults, because the units generate electrical power at voltages of several hundred volts and with currents measured in hundreds of amperes. The same danger also applies to agitators, pumps, feed equipment etc. because these also operate with high levels of electrical power.

The heating and cooling systems of a biogas plant (radiator, digester heater, heat exchanger etc.) also present a risk of scalding in the event of malfunctions. This also applies to parts of the CHP unit and any emergency systems that may be installed (e.g. gas flares).

In order to prevent accidents of this type, clearly visible warning signs must be displayed at the appropriate parts of the plant and the operating personnel must be instructed accordingly.

5.5.2 Environmental protection

5.5.2.1 Hygienisation requirements

The aim of hygienisation is to deactivate any germs and pathogens that may be present in the substrate and thus ensure that it is harmless from the epidemiological and phytohygienic standpoint. This becomes necessary as soon as biogenic wastes from other lines of business are used in addition to raw materials and residues from agriculture.

The relevant underlying legal texts that should be mentioned in this connection are EC Regulation No. 1774/2002 and the Ordinance on Biowastes [5-13]. The EC Regulation includes health rules dealing with the handling of animal by-products not intended for human consumption [5-11]. In biogas plants, subject to official approval category-2 material can be used after high-pressure steam sterilisation (comminution < 55 mm, 133 °C at a pressure of 3 bar for at least 20 minutes [5-12]), manure and digestive tract content can be used without pretreatment, and category-3 material (e.g. slaughterhouse waste) can be used after hygienisation (heating to a minimum of 70 °C for at least 1 hour). This regulation is rarely applied to agricultural biogas plants, however. If the only animal by-products used are catering waste, the regulation is not applicable. If substances are used that are subject to the regulations of the Ordinance on Biowastes, hygienisation is a requirement. In these cases it is necessary to ensure a minimum temperature of 55 °C and a hydraulic dwell time in the reactor of at least 20 days.

5.5.2.2 Air pollution control

Various air pollution control requirements need to be observed in relation to the operation of biogas plants. These requirements relate primarily to odour, pollutant and dust emissions [5-12]. The overarching legal basis is provided by the Federal Pollution Control Act (Bundesimmissionsschutzgesetz – BImSchG) and its implementing regulations together with the Technical Instructions on Air Quality Control (TA Luft). The purpose of the legislation is to protect the environment from harmful effects and to prevent the emergence of such harmful effects. These statutory provisions are applied only within the context of the licensing procedure for large-scale biogas plants with a total combustion capacity of 1 MW or more and for plants designed to treat biowastes.

5.5.2.3 Water pollution control

Harmful impacts on the environment should be avoided if at all possible when operating biogas plants. In relation to water pollution control, in very general terms this means that the biogas plant must be constructed in such a way as to prevent the contamination of surface waters or groundwater. The legal provisions tend to differ from one region to another, since the specific water pollution control requirements depend on the natural conditions at the location in question (e.g. water protection area) and authorities issue approval on a case-to-case basis.

The substances that occur most often at agricultural biogas plants, such as slurry, liquid manure and silage effluent, are categorised in water hazard class 1 (slightly hazardous to water); energy crops are similarly classified [5-14]. The contamination of groundwater and surface water by these substances must there be avoided along the entire process chain. For practical purposes this means that all storage yards, storage tanks and fermentation vessels as well as the pipes and pump feed lines connecting them must be liquid-tight and be of approved design. Particular attention must be paid to silage storage sites, because silage effluent can arise in considerable quantities if harvest conditions are unfavourable and compacting pressures are very high. There is an obligation to collect and make use of the fermentation liquids and effluents escaping from the equipment. As these generally contain considerable quantities of organic materials, it is advisable to feed them into the fermentation tanks. So as not to add unnecessarily large quantities of unpolluted water to the process, especially after heavy precipitation, it makes sense to separate contaminated and uncontaminated water. This can be achieved with separate drainage systems, which use two separate piping systems with manual changeover to divert uncontaminated water to the outfall and contaminated water and effluent to the biogas plant [5-15].

Furthermore, special attention must also be paid to the interfaces between the individual process stages. These include above all the substrate delivery point (solids and liquids) and the discharge of digestates to the transport/application vehicles. The unwanted escape of material (for example overflows or residual quantities of material) must be avoided, or it must be ensured that any contaminated water from these areas is trapped.

In addition, the installation sites for the CHP unit must comply with the relevant regulations, as must the storage locations for new oil, used oil and if applicable ignition oil. It must be possible to identify and eliminate potential leaks of gear oil or engine oil, for example [5-14].

5.5.2.4 Noise abatement

The most common source of noise in relation to biogas plants is traffic noise. The frequency and intensity of the noise generated is mostly dependent on overall plant layout and the input materials used. In the majority of agricultural biogas plants, traffic noise arises in connection with the delivery of substrates (transport, storage and metering system) for a period of 1-2 hours on an almost daily basis. A larger volume of traffic and hence also more noise is to be expected during harvesting and when the substrates are being brought in, and when the fermentation residues are being taken away.

Other noisy machines, for example those operated in connection with the use of gas in a CHP unit, are normally installed in enclosed, soundproofed areas. The legal basis of the regulations relating to noise immissions is provided by the current version of the Technical Instructions on Noise Abatement (TA-Lärm).

5.6 Notes on plant optimisation

The aim of optimisation is to adjust the actual state of a process with regard to a certain property through selective variation of influencing factors in such a way as to achieve a defined target state (the optimum).

In general terms, operation of a biogas plant can be optimised in three areas: technical, economic and environmental (Figure 5.8). These areas cannot be optimised independently of each other; on the contrary, they mutually influence each other. Furthermore, when it comes to solving an optimisation problem it should not be assumed that there will be a single solution, but rather it should be expected that there will be host of different solutions.

The various possible solutions can then be compared with each other on the basis of evaluation criteria. The criteria used for evaluation can include costs, for example, or gas yield, or minimisation of environmental impacts. Depending on the overriding objective the evaluation criteria then need to be weighted, so that a final assessment can be made and a decision taken on which course to follow.

In practice, every responsible operator of a biogas plant should aim to achieve the overall optimum that is attainable under the given general conditions, including those applying specifically to the particular plant. If the conditions change, the operator must assess whether the previous targets can be retained or need to be adapted.

A precondition for optimisation is that the actual state and target state must be defined. Definition of the actual state is achieved by collecting appropriate data in the course of operation of the plant. If it is intended that the plant's own power consumption should be reduced, for example, the operator needs to find out which components contribute to power consumption and what quantities are consumed. The target state can be defined on the basis of planning data, comparable performance data for the technologies used in the plant, publications on the state of the art, information from other operators (e.g. forums, expert discussions etc.) or reports drawn up by independent experts.

Once the actual and target states have been defined, the next steps are to define specific target values, put measures into practice to achieve those targets and subsequently validate the measures to ensure that the targets are achieved and determine possible consequences for other areas of the plant.

In many plants there are shortcomings in relation to the acquisition and documentation of relevant process data in particular, so proper analysis of the actual situation is often not possible. It follows, therefore, too, that only limited data is available for the generation of comparative values. A comprehensive collection of process-relevant data has been assembled as part of the German biogas measuring programmes [5-38], and the KTBL (Association for Technology and Structures in Agriculture) also publishes key performance indicator data pertaining to the operation of biogas plants.

VDI Guideline 4631, Quality criteria for biogas plants, lists the KPIs for process evaluation. It also includes extensive checklists that are useful for data acquisition.

A selection of the parameters that can be used for assessing and subsequently optimising a biogas plant are explained in the following.

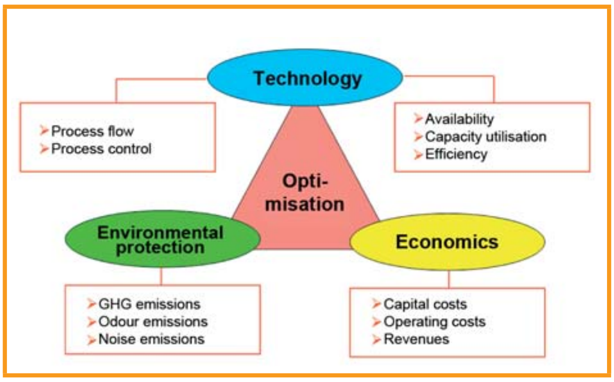

Figure 5.8: Possible optimisations

A general rule when running the plant is that the operating conditions should be kept constant if at all possible. This is the only way that a meaningful actual state can be defined at all. If a change of concept is implemented at the plant, the process targets must be adapted accordingly.

5.6.1 Technical optimisation

The optimisation of technical procedures in a biogas plant is aimed at raising the availability of the technology, in other words at minimising downtimes and ensuring smooth management of the process.

This objective also has indirect consequences for the economics of the plant, of course, because the plant can only meet its performance target if it has a high capacity utilisation rate. On the other hand, a high level of technological input means high cost, so a cost-benefit analysis should be performed in the context of economic optimisation.

As a general rule, in order to assess the availability of the plant as a whole it makes sense to record and document the operating hours and full-load hours. If in addition to that the downtimes and the associated causes of the malfunctions are documented, together with the hours worked and financial cost of correcting the malfunctions, the weak points in the process can be identified.

In very general terms, the availability of technical facilities can be increased by adopting the following regime:

- Keep to maintenance intervals
- Perform predictive maintenance
- Install measuring equipment to detect disturbances
- Stock important spare parts
- Ensure service from the manufacturer or regional workshops is available at short notice
- Use redundant design for critical components
- Use low-wear technologies and materials.

A prerequisite for a stable decomposition process is that the technology remains functional. If outages occur during charging of the digester or during mixing, the biological process is directly affected. For more details of optimising the biological process, see chapter 2 and the relevant sections of this chapter.

5.6.2 Analysing the efficiency of the plant as a whole (utilisation of substrate on the basis of energy flows)

If the plant is operating at a high utilisation rate, in certain circumstances it may be possible to increase efficiency by looking at the plant's power demand and investigating and if possible reducing any energy losses. It makes sense here to consider the plant as a whole in order to identify the key energy flows and weak points. The following separate areas need to be taken into consideration:

- Substrate supply (quantity and quality of the substrate, quality of ensilage, feeding of the substrate)
  - Silage loss (quality of ensilage, feed rate, size of cut surfaces, seepage water)
- Process biology (feeding intervals, degree of degradation achieved, specific biogas production rate and composition, stability of the plant, substrate composition, acid concentrations)
- Gas utilisation (efficiency of the CHP unit (electrical and thermal), methane slip, engine settings, maintenance intervals)
- Fermentation residue (residual gas potential of the fermentation residue, utilisation of the fermentation residue)
- Methane losses (emissions from leakage)
- Workload for plant operation and troubleshooting, downtimes
- On-site energy consumption
  - Regular acquisition of meter readings (energy consumption, running times)
  - Clear demarcation between power consumers (e.g. agitators, loading system, CHP unit …)
  - Adjustment of agitator systems, agitator running times and agitation intensity to the conditions
  - No pumping of unnecessary quantities
  - Efficient and economical substrate treatment and loading technologies
- Heat recovery concept.

It should always be remembered that each biogas plant is a system that consists of a large number of individual components that have to be fine-tuned to each other. Efforts must therefore be made as early as the planning phase to ensure that the chain works as a unified whole: purchasing individual components that work does not necessarily produce a working biogas plant.

It is often seen in practice that somewhere along the process chain there is a bottleneck that restricts performance and hence the economic efficiency of the downstream plant components. It may be the case, for example, that gas generation output does not reach the capacity of the CHP unit, but by taking steps such as changing the substrate mixture or improving capacity utilisation in the second digester stage it could be possible to achieve the required level of gas production.

In addition to the balancing of energy flows, therefore, balancing material flows is also an appropriate means of discovering deficiencies in plant operation.

5.6.3 Economic optimisation

Economic optimisation is aimed at reducing costs and increasing yields. Like technical optimisation, economic optimisation can be applied to all sub-processes. In this case, too, the first step is to identify the substantial cost factors so that the related costs can be reduced accordingly.

Specific variables such as electricity generation costs (e.g. in €/kWh) or specific investment costs (in €/kWel inst.) serve as the basis for an initial guide to plant performance as a whole. There are comparative studies for these (for example German biogas measuring programme, [5-38]), thus enabling the overall economic performance of the plant to be graded. To conduct an in-depth study it is advisable to analyse and compare the following economic data:

- Operating costs
  - Personnel costs
  - Maintenance costs
  - Repair costs
  - Energy costs
  - Cost of upkeep
- Investment costs (depreciation), repayment, interest
- Substrate costs (linked to substrate quality and substrate quantities)
- Revenue for generated electricity and heat
- Revenue for substrates
- Revenue for fermentation residues/fertiliser.

5.6.4 Minimisation of environmental impacts

The minimisation of environmental impacts aims at reducing the effects of the plant on the environment. The release of pollutants to the air, water and soil needs to be considered.

- Seepage water (collection and utilisation of silage seepage water, runoff from storage areas)
- Methane emissions from the biogas plant (provide digestate storage tank with gas-tight cover, identify leaks, slip from gas utilisation, engine settings, maintenance work)
- Formaldehyde, NO_x, oxides of sulphur, carbon monoxide (CHP unit only, engine settings, exhaust gas treatment)
- Odour emissions (covered loading facility, storage areas and digestate storage tank, separated fermentation residues)
- Noise emissions
- After the application of fermentation residues: ammonia emissions, nitrous oxide emissions (appli-

cation techniques and incorporation of the residues).

Not only do uncontrolled emissions of silage seepage water, methane and ammonia have a detrimental impact on the environment, they also signify losses in terms of the efficiency of the plant as a whole. In this respect, structural or operational measures to reduce emissions can certainly pay off financially (for example a gas-tight cover for a digestate storage tank). As a general rule the plant should be regularly checked for possible emissions. In addition to environmental and economic considerations, it is often also necessary to take safety matters into account as well.

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Gas processing and options for utilisation

6

At present, the most common use of biogas in Germany is for the raw gas to be converted locally into electricity at its place of origin. In most cases this involves the use of an internal combustion engine to drive a generator, which in turn produces electricity. It is also possible to make use of biogas in gas microturbines, fuel cells and Stirling engines. These technologies also primarily serve the purpose of converting biogas into electricity, but to date they have rarely been put into practice. Another possible use of biogas involves the recovery of thermal energy in suitable burners or heating boilers.

In addition, in recent years the option of biogas treatment with subsequent feed-in to the natural gas grid has become increasingly common. In August 2010 there were already 38 plants feeding treated biomethane into the natural gas grid [6-9]. Numerous other projects will be implemented in the coming years. In this connection it is worth mentioning the ambitious targets set by the German Government, which call for six billion cubic metres of natural gas to be substituted with biogas each year by the year 2020. As an alternative to grid feed-in it is also possible to use biomethane directly as a fuel, although so far this has been done on only a small scale in Germany.

As a rule it is not possible to make direct use of the raw gas obtained from a biogas plant because of the various biogas-specific constituents in the gas, such as hydrogen sulphide. For this reason the biogas is passed through various purification stages, different combinations of which are a prerequisite for the utilisation options mentioned at the start of this chapter.

6.1 Gas purification and gas processing

Raw (or crude) biogas is saturated with water vapour, and in addition to methane (CH_4) and carbon dioxide (CO_2) it also includes significant quantities of hydrogen sulphide (H_2S), among other things.

Hydrogen sulphide is toxic and has an unpleasant smell of rotten eggs. The hydrogen sulphide and water vapour contained in biogas combine to form sulphuric acid. The acids corrode the engines in which the biogas is used, as well as the components upstream and downstream of the engine (gas pipe, exhaust gas system, etc.). The sulphur constituents also diminish the performance of downstream purification stages (CO_2 removal).

For these reasons, the biogas obtained from agricultural biogas plants is normally desulphurised and dried. However, depending on the accompanying substances contained in the biogas or the chosen utilisation technology (e.g. use as a substitute for natural gas), there may be a need for further treatment or processing of the gas. The manufacturers of CHP units have minimum requirements for the properties of the fuel gases that can be used. The same applies to the use of biogas. The required fuel gas properties should be complied with in order to avoid increased frequency of maintenance and to prevent engine damage.

6.1.1 Desulphurisation

A variety of methods are used for desulphurisation. A distinction can be drawn between biological, chemical and physical desulphurisation methods as well as between rough and fine desulphurisation, depending on the application. The method, or combination of methods, used will depend on how the biogas is to be subsequently utilised. A comparative overview of the methods under consideration is given in Table 6.1.

Table 6.1: Overview of desulphurisation methods [6-32]

Method	Energy demand		Consumables		Air injection	Purity in ppmv	DVGW satisfied? [a]	Problems
	el.	therm.	Consumption	Disposal				
Biological desulphurisation in digester	++	o	++	++	Yes	50-2,000	No	Imprecise process control
External biological desulphurisation	-	o	+	+	Yes	50-100	No	Imprecise process control
Bioscrubber	-	o	-	+	No	50-100	No	High process cost and complexity
Sulphide precipitation	o	o	--	o	No	50-500	No	Sluggish process
Internal chemical desulphurisation	o	o	--	--	Yes	1-100	No	Greatly diminishing purification effect
Activated carbon	o	o	--	-	Yes	< 5	Yes	Large disposal volumes

a. according to DVGW Code of Practice G 260
++ particularly advantageous, + advantageous, o neutral, - disadvantageous, -- particularly disadvantageous

Table 6.2: Characteristic values and process parameters for biological desulphurisation in the digester

Characteristic values	• Air supply 3-6 vol. % of the released biogas volume
Suitability	• All digesters with sufficient gas space above the digester • No point in subsequent feed-in to natural gas grid
Advantages	+ Highly cost-efficient + Use of chemicals not required + Low-maintenance and reliable technology + Sulphur drops back into the digestate and can therefore be applied to fields as fertiliser
Disadvantages	- No relationship to the amount of hydrogen sulphide actually released - Selective optimisation of hydrogen sulphide removal impossible - Possible process interference and methane oxidation by introduction of oxygen - Day/night and seasonal variations in temperature in the gas space can have an adverse effect on desulphurisation performance - Not possible to respond to fluctuations in the quantity of gas released - Corrosion in the digester and risk of formation of explosive gas mixtures - Not suitable for upgrading to natural gas quality - Reduction of calorific value/heating value
Special features	• Growth surfaces for the sulphur bacteria should be available or additionally created, because the existing surface area is not usually sufficient for desulphurisation • Optimisation can be achieved by controlling the supply of oxygen to the reactor and continuous measurement of hydrogen sulphide
Designs	• Mini compressor or aquarium pump with downstream control valve and flow indicator for manual control of gas flow
Maintenance	• Barely necessary

Apart from the composition of the gas, it is above all the flow rate of the biogas through the desulphurisation facility that is a key factor. This can fluctuate considerably, depending on how the process is managed. Particularly high temporary biogas release rates and consequent high flow rates can be observed after fresh substrate has been loaded into the digester and during operation of the agitators. It is possible for short-term flow rates to be 50% above the average. In order to ensure reliable desulphurisation it is common practice to install oversized desulphurisation units or to combine different techniques.

6.1.1.1 Biological desulphurisation in the digester

Biological desulphurisation is often performed in the digester, although downstream processes are also conceivable. In the presence of oxygen, the bacterium *Sulfobacter oxydans* converts hydrogen sulphide into elemental sulphur, which is subsequently discharged from the reactor in the digestate. The conversion process requires nutrients, adequate quantities of which are available in the digester. As the bacteria are omnipresent, they do not need to be specially added. The necessary oxygen is provided by air being injected into the digester, for example by being blown in using a mini compressor (e.g. an aquarium pump). The quality obtained in this way is usually sufficient for combustion of the desulphurised gas in a combined heat and power unit. It is only when there are considerable variations of concentration in the raw gas that it is possible for breakthrough sulphur concentrations to occur, which can have adverse consequences for the CHP unit. On the other hand, this method is not suitable for upgrading to natural gas quality as it is difficult to remove the higher concentrations of nitrogen and oxygen, which worsens the combustion properties of the gas. The characteristic values of biological desulphurisation in the digester are shown in Table 6.2, and an example of an installation is presented in Figure 6.1.

6.1.1.2 Biological desulphurisation in external reactors – trickling filter process

In order to avoid the drawbacks outlined above, biological desulphurisation can also be performed outside the digester, using the trickling filter process. Some companies offer biological desulphurisation columns for this purpose, which are arranged in separate tanks. This makes it possible to comply more accurately with the parameters needed for desulphurisation, such as the supply of air/oxygen. In order to increase the fertilising effect of the digested substrate, the arising sulphur can be re-added to the digested substrate in the digestate storage tank.

The trickling filter process, in which hydrogen sulphide is absorbed with the aid of a scrubbing medium (regeneration of the solution by admixture of atmospheric oxygen), can attain removal rates of up to 99%, which can result in residual gas concentrations of less than 50 ppm sulphur [6-24]. Because of the large amount of air introduced, approximately 6%, this method is not suitable for use for biomethane processing [6-5].

Figure 6.1: Gas control system for injecting air into the digester gas space [DBFZ]

6.1.1.3 Biochemical gas scrubbing – bioscrubbers

In contrast to the trickling filter process and internal desulphurisation, bioscrubbing is the only biological process that can be used to upgrade biogas to the quality of natural gas. The two-stage process consists of a packed column (absorption of the H_2S by means of dilute caustic soda solution), a bioreactor (regeneration of the scrubbing solution with atmospheric oxygen) and a sulphur separator (discharge of elemental sulphur). Separate regeneration means that no air is introduced into the biogas. Although very high sulphur loads can be eliminated (up to 30,000 mg/m^3), with similar results to those of a trickling filter system, this technology is only suitable for plants with high gas flows or high H_2S loads because of the high cost of the equipment. The characteristics are shown in Table 6.4.

6.1.1.4 Sulphide precipitation

This form of chemical desulphurisation takes place in the digester. Like the biological desulphurisation methods, it is used for rough desulphurisation (H_2S values between 100 and 150 ppm are achievable [6-35]). The addition of iron compounds (given in Table 6.5) to the digester chemically binds the sulphur in the digestion substrate, thereby preventing sulphur from being released as hydrogen sulphide. Given the characteristics listed in Table 6.5, this method is primarily suited to relatively small biogas plants or to plants with low H_2S loading (< 500 ppm) [6-35].

Table 6.3: Characteristic values and process parameters for external biological desulphurisation units

Characteristic values	• Removal efficiency of over 99% possible (e.g. from 6,000 ppm to < 50 ppm) • Available for all sizes of biogas plant
Suitability	• All biogas production systems • Rough desulphurisation • Trickling filter column not suitable for feed-in
Advantages	+ Can be sized to suit the amount of hydrogen sulphide actually released + Selective automated optimisation of hydrogen sulphide removal can be achieved by management of nutrients, air supply and temperature + No interference with the process through introduction of oxygen into the digester (as the air is introduced outside the digester) + Use of chemicals not required + Technology can easily be retrofitted + If unit is large enough, short-term fluctuations in gas volume have no negative impact on gas quality
Disadvantages	- Additional unit with associated costs (thermal optimum of trickling filter unit at 28–32 °C) - Need for additional maintenance (supply of nutrients) - Trickling filter units with excessive introduction of air into biogas
Special features	• External desulphurisation units
Designs	• As columns, tanks or containers made of plastic or steel, free-standing, packed with filter media, sometimes with backwashing of microorganism emulsion (trickling filter process)
Maintenance	• In some cases biological microorganism emulsions have to be replenished at lengthy intervals or filter media require long-term replacement

Figure 6.2: External biological desulphurisation columns, to the right of a gas holder [S&H GmbH & Co. Umweltengineering KG]

6.1.1.5 Adsorption on activated carbon

Adsorption on activated carbon, which is used as a fine desulphurisation technique, is based on catalytic oxidation of the hydrogen sulphide on the surface of the activated carbon. The reaction rate can be improved and the loading capacity increased by impregnating or doping the activated carbon. Potassium iodide or potassium carbonate can be used as impregnating material. Adequate desulphurisation requires the presence of water vapour and oxygen. Impregnated activated carbon is therefore not suitable for use with air-free gases. However, the doped activated carbon (potassium permanganate) that has recently appeared on the market can also be used for gas-free biogases. This also improves the desulphurisation performance, because there is no blocking of the micropores [6-35].

6.1.2 Drying

In order to protect the gas utilisation equipment from severe wear and destruction and to meet the requirements of the downstream purification stages, water vapour must be removed from the biogas. The amount of water or water vapour that biogas can take up depends on the temperature of the gas. The relative humidity of biogas in the digester is 100%, which means that the biogas is saturated with water vapour. The methods that enter into consideration for the drying of biogas are condensation drying, adsorption drying (silica gel, activated carbon) and absorption drying (glycol dehydration). These methods are briefly explained in the following.

6.1.2.1 Condensation drying

The principle of this method is based on the separation of condensate by cooling the biogas to below the dew point. The biogas is often cooled in the gas pipe. Provided the gas pipe is installed with an appropriate gradient, the condensate is collected in a condensate separator fitted at the lowest point of the gas pipe. If the gas pipe is buried, the cooling effect is greater. For the

Table 6.4: Characteristic values and process parameters for external biochemical gas scrubbers

Characteristic values	• Can be used with caustic soda solution or iron hydroxide • Systems available for gas flows between 10 and 1,200 Nm^3/h • Depending on how the raw gas volume and plant size are matched, very high degrees of purification can be achieved, above 95%
Suitability	• All biogas production systems • Rough desulphurisation
Advantages	+ Can be sized to suit the amount of hydrogen sulphide actually released + Selective automated optimisation of hydrogen sulphide separation can be achieved by management of scrubbing solutions and temperature + No detrimental effect on the process as a result of introduction of oxygen + Avoidance of serious corrosion of components in the gas space of the digester (in comparison with internal biological desulphurisation)
Disadvantages	- Additional equipment with associated costs (caustic soda solution, fresh water) - Chemicals required - Additional fresh water required for dilution of solution (not needed with iron hydroxide) - Need for additional maintenance
Special features	• Although spent solution must be disposed of in a wastewater treatment plant, no problems from a chemical standpoint (applies only to caustic soda solution) • External desulphurisation unit
Designs	• As columns or tanks made of plastic, free-standing, packed with filter media, with backwashing of solution
Maintenance	• Chemicals need replenishing at lengthy intervals • Iron hydroxide can be repeatedly regenerated by aeration with ambient air, although the high release of heat can cause ignition

Table 6.5: Characteristic values and process parameters for internal chemical desulphurisation; after [6-13]

Characteristic values	• Chemical substances used for removal can be iron salts (iron(III) chloride, iron(II) chloride, iron(II) sulphate) in solid or liquid form; bog iron ore is also suitable • Guide value according to [6-20]: addition of 33 g Fe per m^3 substrate
Suitability	• All wet digestion systems • Rough desulphurisation
Advantages	+ Very good removal rates + No additional unit required for desulphurisation + No need for additional maintenance + Substances can be dosed relative to the feedstock mass + No detrimental effect on the process as a result of introduction of oxygen + Avoidance of serious corrosion of components in the gas space of the digester (in comparison with internal biological desulphurisation) + Fluctuations in the gas release rate do not cause a loss of quality in the biogas + This method with downstream fine desulphurisation suitable for biogas feed-in to grid
Disadvantages	- Difficult to match dimensions to sulphur content of the feedstock (overdosing usually necessary) - Increased running costs as a result of continuous consumption of chemicals - Increased capital expenditure due to more extensive safety measures
Special features	• Chemical desulphurisation in the digester is sometimes used when biological desulphurisation in the gas space of the digester is insufficient • Resulting iron sulphide can cause sharp rise in iron concentration in soil after application to fields
Designs	• Manual or automated dosing by additional small-scale conveying equipment • Introduction as a solution or in the form of pellets and grains
Maintenance	• Little or no maintenance required

biogas to be cooled in the gas pipe, however, the pipe needs to be long enough to allow sufficient cooling. In addition to water vapour, some other unwanted constituents, such as water-soluble gases and aerosols, are also removed from the biogas with the condensate. The condensate separators must be drained at regular intervals, for which reason they have to be easily accessible. It is essential to prevent the condensate separators from

Table 6.6: Characteristic values for desulphurisation by means of activated carbon

Characteristic values	• Use of impregnated (potassium iodide, potassium carbonate) or doped (potassium permanganate) activated carbon
Suitability	• All biogas production systems • For fine desulphurisation with loadings of 150 to 300 ppm
Advantages	+ Very good removal rates (< 4 ppm is possible [6-25]) + Moderate capital expenditure + No detrimental impact on the process as a result of the introduction of oxygen in the case of doped activated carbon + Avoidance of serious corrosion of components in the gas space of the digester (in comparison with internal biological desulphurisation) + Method suitable for biogas feed-in to grid
Disadvantages	- Not suitable for oxygen-free and water-vapour-free biogases (exception: impregnated activated carbon) - High operating costs because of expensive regeneration (steam at temperatures above 450 °C [6-4]) - Disposal of activated carbon - Use of selected sulphur not possible
Special features	• Desulphurisation with activated carbon is used when especially low-sulphur gases are required
Designs	• As columns made of plastic or stainless steel, free-standing, packed with activated carbon
Maintenance	• Regular replacement of activated carbon required

freezing by installing them in a frost-free location. Additional cooling can be obtained by the transfer of cold by cold water. According to [6-35], this method can be used to achieve dew points of 3-5 °C, which enables the water vapour content to be reduced to as little as 0.15 vol. % (initial concentration: 3.1 vol. %, 30 °C, ambient pressure). Prior compression of the gas can further improve these effects. The method is considered state of the art for subsequent combustion of the gas. However, it only partially satisfies the requirements for feed-in to the gas grid, because the requirements of DVGW Codes of Practice G260 and G262 cannot be met. Downstream adsorptive purification techniques (pressure swing adsorption, adsorptive desulphurisation methods) can remedy this problem, though [6-35]. Condensation drying is suitable for all flow rates.

6.1.2.2 Adsorption drying

Significantly better drying results can be achieved with adsorption processes, which work on the basis of zeolites, silica gels or aluminium oxide. Dew points down to -90 °C are possible in this case [6-22]. The adsorbers, which are installed in a fixed bed, are operated alternately at ambient pressure and 6-10 bar, and are suitable for small to medium flow rates [6-35]. The adsorber materials can be regenerated by either heatless or heated regeneration. More detailed information about regeneration can be found in [6-22] or [6-35]. Thanks to the results that can be attained, this method is suitable for all possible uses.

6.1.2.3 Absorption drying

Glycol dehydration is a technique used in natural gas processing. It is an absorptive and hence physical process for counterflow injection of glycol or triethylene glycol into biogas in an absorber column. This allows both water vapour and higher hydrocarbons to be removed from the raw biogas. In the case of glycol scrubbing, regeneration is carried out by heating the scrubbing solution to 200 °C, which causes the impurities to evaporate [6-37]. In the literature, -100 °C is given as an attainable dew point [6-30]. From an economic standpoint this method is suitable for relatively high flow rates (500 m^3/h) [6-5], which makes biogas feed-in the main subsequent utilisation option for consideration.

6.1.3 Carbon dioxide removal

Carbon dioxide removal is a necessary processing stage above all where the product gas is subsequently to be fed into the grid. Increasing the methane concentration makes it possible to adjust the combustion properties to the values required in the DVGW Code of Practice. Since 2006, 38 plants that feed processed biogas into the natural gas grid have begun operation in Germany. Both in Germany and in other European countries, the most commonly used processing methods are water scrubbing and pressure swing adsorption, followed by chemical scrubbing. The factors determining the choice of method are the gas properties, achievable quality of the product gas, methane

Table 6.7: Comparison of methane enrichment methods [6-5], [6-35]

Method	Mode of action/characteristics	Achievable CH_4 concentration	Comments
Pressure swing adsorption (PSA)	Alternating physical adsorption and desorption by changes in pressure	> 97%	Large number of projects implemented, prior desulphurisation and drying required, little scope for regulation of system, high power requirements, no heat requirements, high methane slip, no process chemicals
Water scrubbing	Physical absorption with water as solvent; regeneration by pressure reduction	> 98%	Large number of projects implemented, no upstream desulphurisation and drying required, flexible adaptation to gas flow rate, high power requirements, no heat requirements, high methane slip, no process chemicals
Amine scrubbing	Chemical absorption using scrubbing liquors (amines), regeneration with H_2O vapour	> 99%	Some projects implemented, for low gas flow rates, low power requirements (pressureless process), very high heat requirements, minimal methane slip, high scrubbing agent requirements
Genosorb scrubbing	Similar to water scrubbing but with Genosorb (or Selexol) as solvent	> 96%	Few projects implemented, advisable for large plants on economic grounds, no upstream desulphurisation and drying required, flexible adaptation to gas flow rate, very high power requirements, low heat requirements, high methane slip
Membrane separation methods	With pore membranes: pressure gradient for gas separation, otherwise diffusion rate of gases	> 96%	Few projects implemented, prior desulphurisation and drying required, very high power requirements, no heat requirements, high methane slip, no process chemicals
Cryogenic methods	Gas liquefaction by rectification, low-temperature separation	> 98%	Pilot plant status, prior desulphurisation and drying required, very high power requirements, very low methane slip, no process chemicals

losses and, finally, the processing costs, which can vary depending on local circumstances. The key characteristics of the processing methods are summarised in Table 6.7, and are explained in more detail in the following sections.

6.1.3.1 Pressure swing adsorption (PSA)

Pressure swing adsorption (PSA) is a technique that uses activated carbon, molecular sieves (zeolites) and carbon molecular sieves for physical gas separation. This method is considered state of the art and is frequently applied. Many projects have been executed with this technology to date, especially in Germany. Depending on the duration of the four cycles for adsorption (i.e. take-up of H_2O vapour and CO_2 at a pressure of approx. 6 to 10 bar), desorption (by pressure relief), evacuation (i.e. further desorption by flushing with raw gas or product gas) and pressure build-up, between four and six adsorbers are connected in parallel for biogas processing plants. This plant configuration achieves CH_4 yields of around 97 vol. %. The methane yield can be further increased, at extra cost, by introducing additional flushing cycles with raw gas and/or product gas and partial recirculation of the waste gas upstream of the compressor. Given proper use of the system, the useful life of the adsorbents is almost unlimited, although this requires the raw gas to be sulphur-free and dried. Water, hydrogen sulphide and any other minor components would otherwise be adsorbed on the carbon molecular sieves and the PSA separation efficiency would be permanently impaired or separation would come to a complete standstill. Total energy demand is quite low in comparison with other methods, although electric power demand is relatively high because of the constant pressure changes. Another advantage is that this method is ideal for small capacities. The disadvantage of PSA is that, at present, there are relatively high methane losses in the exhaust air stream (approx. 1-5%). In view of the considerable impact of methane as a greenhouse gas, post-oxidation of the exhaust air is required.

6.1.3.2 Water scrubbing

High-pressure water scrubbing is the most widespread method for processing biogas in Europe (roughly 50% of all plants). It makes use of the different solubilities of CH_4 and CO_2 in water. Pretreated biogas (i.e. after removal of any water droplets entrained from the digester or mist in gravel packing) is compressed first to about 3 bar and in a subsequent stage to about 9 bar before it streams in counterflow through the H_2O-charged absorption column (trickling bed reactor) [6-5]. In the column, hydrogen sulphide, carbon dioxide and ammonia as well as any particulates and microorganisms in the raw gas are dissolved in the water. These substances are removed from the system after the water pressure is subsequently reduced. Upstream desulphurisation/drying is not necessary with this method. A further advantage of the method is its high degree of flexibility. Not only pressure and temperature but also plant throughput (adjustable between 40% and 100% of the design capacity) can be controlled depending on the CO_2 concentration of the raw gas [6-5]. Other positive aspects include continuous and fully automatic operation, ease of maintenance, ability to process moisture-saturated gas (possible by subsequent drying), field-proven reliability, coabsorption of H_2S and NH_3 and use of water as absorbent (freely available, safe and low-cost) [6-5]. The disadvantages of the method are its high power requirements and comparatively high methane slip (approx. 1%), which means that post-oxidation is required.

6.1.3.3 Chemical scrubbing (amine)

Amine scrubbing is a chemical absorption process in which the unpressurised biogas is brought into contact with a scrubbing liquid, with the carbon dioxide being transferred to the scrubbing medium. Scrubbing media often used for CO_2 removal are monoethanolamine (MEA) (in low-pressure processes and where the only substance to be removed is CO_2) and diethanolamine (DEA) (in high-pressure processes without regeneration). Methyldiethanolamine (MDEA) or sometimes triethanolamine (TEA) is used for separation of CO_2 and H_2S [6-5]. To recover the scrubbing agent, a desorption or regeneration stage is included downstream of the absorption stage, usually using water vapour. This results in a high demand for thermal energy, which is the major drawback of this process. The greatest potential for optimisation of this technology therefore lies in the implementation of clever heating concepts. The continuous consumption of solvent as a result of incomplete regeneration is another disadvantage. On the other hand, amine scrubbing has the advantage that very high-quality product gas (> 99%) can be obtained with very low methane slip (< 0.1%). In the past this process has been used only occasionally in Germany and Europe, but now in Germany in particular the number of amine scrubbing plants is growing.

Amine scrubbing is mainly used for low flow rates and at locations with favourable sources of heat.

6.1.3.4 Physical scrubbing (Selexol, Genosorb)

The Genosorb process, which is a further development of the Selexol process, works according to a principle similar to that of high-pressure water scrubbing. Instead of water, in this case a scrubbing solution (Genosorb) is brought into contact with the biogas at 7 bar. In addition to carbon dioxide and hydrogen sulphide, the process can also be used to remove water. Genosorb scrubbing is therefore the only method capable of removing all three impurities in a single process step. For economic reasons, however, it makes sense to use desulphurised and dried biogas. Regeneration of the scrubbing solution takes place at 50 °C through step-by-step pressure reduction and subsequent flushing with ambient air. The required heat can be made available by extracting the waste heat from gas compression, according to [6-35]. The manufacturer quotes a figure of 1 to 2% for methane slip, which requires post-treatment with the aid of a thermal oxidation stage. From an energy standpoint, this method has a slightly higher energy requirement than water scrubbing or pressure swing adsorption [6-35].

6.1.3.5 Membrane processes

Membrane technology is a relatively new approach in biogas processing and is currently still at the development stage, although a few membrane separation systems are already in use (for example in Austria and Kisslegg-Rahmhaus). In terms of process engineering, membrane techniques bring about the separation of methane and other gas components by making use of the different diffusion rates of the variously sized gas molecules. Methane, which is a relatively small molecule, diffuses more quickly through most membranes than carbon dioxide or hydrogen sulphide, for example. The purity of the gas can be adjusted by the choice of membrane type, membrane surface, flow rate and number of separation stages.

6.1.3.6 Cryogenic separation

Cryogenic gas processing (i.e. the separation of CH_4 and CO_2 at low temperature) includes not only rectification (gas liquefaction), in which liquid CO_2 is produced, but also low-temperature separation, which causes the CO_2 to freeze [6-5]. Both are technically

Figure 6.3: Biogas treatment plant (Genosorb scrubbing) in Ronnenberg [Urban, Fraunhofer UMSICHT]

highly demanding processes which require the gas to be first desulphurised and dried. Especially with regard to their application for biogas, these processes have not been tried and tested in the field. The biggest problem with the method is the large amount of energy required. However, the attainable gas qualities (> 99%) and low methane losses (< 0.1%) suggest that further development would be worthwhile.

6.1.4 Oxygen removal

Removing oxygen from the raw biogas may be important where biomethane is to be fed into the natural gas grid. In addition to the DVGW Codes of Practice, it is also necessary in this case to take account of transnational agreements. The processing methods that have become best established in this connection are catalytic removal with palladium-platinum catalysts and chemisorption with copper contacts. Further information is given in [6-35].

6.1.5 Removal of other trace gases

The trace gases found in biogas include ammonia, siloxanes and BTX (benzene, toluene, xylene). High levels of these substances are not expected to occur in agricultural biogas plants, however. As a rule, the loadings are below the levels stipulated by the DVGW Codes of Practice [6-35], and are in fact only detectable at all in a few cases. Apart from that, these substances are also removed in the course of the above-described purification processes of desulphurisation, drying and methane enrichment.

6.1.6 Upgrading to natural gas quality

Where biogas is to be fed into a grid, having passed through the individual purification stages the treated biogas must be finally adjusted to meet the required natural gas quality specifications. Although these are determined by the properties of the available natural gas, as far as the biogas producer is concerned all that counts is compliance with DVGW Codes of Practice G 260 and G 262. It is the grid operator, however, who is responsible for fine adjustment as well as for ongoing operating costs (for further information see Section 7.4.3). The points that need to be taken into consideration at this stage are explained below.

6.1.6.1 Odorisation

As biomethane, which is odourless, must be detectable by the senses in the event of a leak, odorants need to be continuously added. Sulphurous organic compounds such as mercaptans or tetrahydrothiophene (THT) are mainly used for this purpose. In recent years, however, there has been a discernible trend towards sulphur-free odorising agents, for ecological and technical reasons. Odorants can be admixed by injection or through a bypass arrangement. Precise details of the technology for monitoring of odorisation are given in DVGW Code of Practice G 280-1.

6.1.6.2 Adjustment of calorific value

The biomethane that is fed into the grid must have the same combustion properties as the natural gas in the pipeline. Measures of these properties include the calorific value (heating value), relative density and Wobbe index. These values must lie within the permissible ranges, although the relative density may temporarily exceed the allowed maximum value and the Wobbe index may temporarily fall below its allowed minimum value. Precise details are given in DVGW Codes of Practice G 260 and G 685. Adjustment of the parameters can be achieved by adding air (if the calorific value of the biogas is too high) or liquefied gas, usually a propane-butane mixture (if the calorific value of the biogas is too low). The admixture of liquefied gas is limited firstly by the risk of its reliquefaction in high-pressure applications connected to the grid (storage tanks, CNG filling stations) and secondly by the stipulations laid down in DVGW Code of Practice G 486. Because of the limits of the mathematical methods used for conversion, the maximum amounts of propane and butane to be added are restricted to 5 and 1.5 mol% respectively.

6.1.6.3 Adjustment of pressure

Pressure slightly above grid pressure is required in order to inject the biomethane into the various grid levels. The possible injection levels are low-pressure grids (< 0.1 bar), medium-pressure grids (0.1 to 1 bar) and high-pressure grids (1 bar or over). Pressures of 16 bar or more are referred to as super pressure [6-5].

Screw compressors or reciprocating compressors are often used for compressing biogas. It should be noted that some processes (PSA, water scrubbing) already deliver the treated biogas at an operating pressure of 5 to 10 bar, which means that, depending on the grid pressure, there may be no need for an additional compressor station.

6.2 Utilisation for combined heat and power

Combined heat and power (CHP), or cogeneration, refers to the simultaneous generation of both heat and electricity. Depending on the circumstances, a distinction can be drawn between power-led and heat-led CHP plants. The heat-led type should normally be chosen, because of its higher efficiency. In almost all cases this means using small-scale packaged CHP units with internal combustion engines coupled to a generator. The engines run at a constant speed so that the directly coupled generator can provide electrical energy that is compatible with system frequency. Looking into the future, for driving the generator it will also be possible to use gas microturbines, Stirling engines or fuel cells as alternatives to the conventional pilot ignition gas engines and gas spark ignition engines.

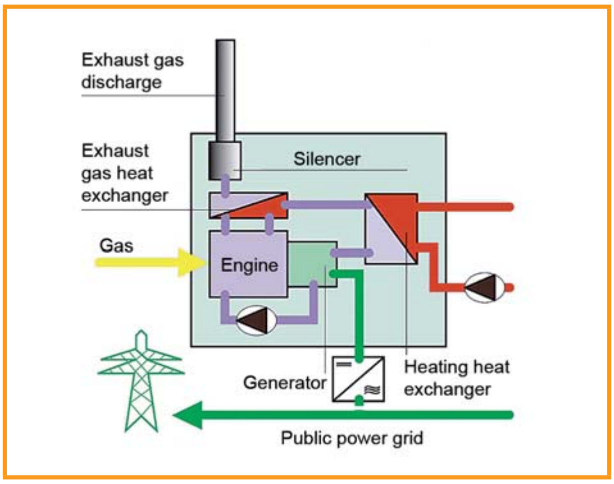

Figure 6.4: Schematic layout of a CHP unit [ASUE]

6.2.1 Small-scale packaged CHP units with internal combustion engines

In addition to an internal combustion engine and an appropriately matched generator, a CHP module consists of heat exchanger systems for the recovery of

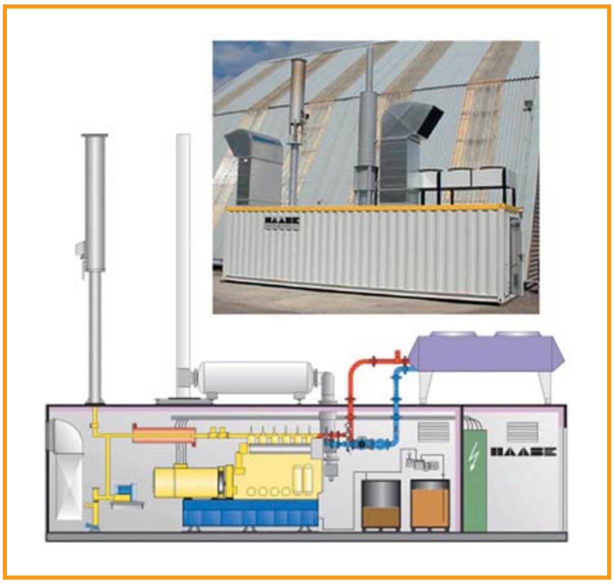

Figure 6.5: Biogas CHP unit, compact stand-alone module with emergency flare [Haase Energietechnik AG]

thermal energy from exhaust gas, cooling water and lubricating oil circuits, hydraulic systems for heat distribution and electrical switching and control equipment for power distribution and control of the CHP unit. The engines used in such units are either gas spark ignition or pilot ignition gas engines. While the latter have been more commonly used in the past, two or three new plants have been fitted with gas spark ignition engines, which are operated according to the Otto principle without additional ignition oil; the only difference is in the compression. The schematic layout of a biogas CHP unit and an example of a plant are shown in Figures 6.4 and 6.5 respectively.

6.2.1.1 Gas spark ignition engines

Gas spark ignition engines are engines that operate according to the Otto principle and that have been specially developed to run on gas. To minimise nitrogen oxide emissions, the engines are run as lean-burn engines with high excess air levels. In lean-burn mode less fuel can be converted in the engine, which results in a reduction in power. This is compensated for by turbocharging the engine using an exhaust turbocharger. A gas spark ignition engine relies on a minimum concentration of roughly 45% methane in the biogas. If the methane concentration is lower, the engine shuts down.

If no biogas is available, a gas spark ignition engine can also run on other types of gas, such as natural gas [6-12]. This may be useful, for example, for starting up the biogas plant in order to make the necessary process heat available via the waste heat from the engine. In addition to the gas control train for the biogas, a separate control train must be installed for the substitute gas.

The key parameters of gas spark ignition engines relevant to their use with biogas are shown in Table 6.8.

6.2.1.2 Pilot ignition gas engines

Pilot ignition gas engines operate according to the principle of a diesel engine. They are not always specially developed to run on gas and thus have to be modified. The biogas is added to the combustion air via a gas mixer and is ignited by the ignition oil, which is supplied to the combustion chamber by an injection system. The adjustment is usually such that the ignition oil concentration accounts for about 2-5% of the supplied fuel power. Because of the relatively small amount of injected ignition oil, the lack of cooling of the injection nozzles means that there is a risk that they will suffer from coking [6-12] and therefore wear more quickly. Pilot ignition gas engines are also operated with high excess air levels. Load regulation is by controlling the quantity of ignition oil or gas supplied.

If the supply of biogas becomes unavailable, pilot ignition gas engines can run on ignition oil or diesel. Changing over to substitute fuels can be done without difficulty, and may be necessary when starting up the biogas plant in order to provide process heat.

According to the Renewable Energy Sources Act (EEG), only ignition oils from renewable sources, such as rape methyl ester or other approved types of biomass, can be considered for use as ignition oil. The engine manufacturers' quality requirements must be met, however. The characteristic values and process parameters of pilot ignition gas engines are shown in Table 6.9.

6.2.1.3 Reduction of pollutants and exhaust gas treatment

Stationary combustion engine plants designed for use with biogas are classified as being licensable under the provisions of the Federal German Pollution Control Act (BImSchG) if the rated thermal input is 1 MW or higher. The Technical Instructions on Air Quality Control (TA Luft) specify relevant emission standards, which must be observed. If the installed rated thermal input is below 1 MW, the plant is not licensable under BImSchG. In this case the values specified in TA Luft

Table 6.8: Characteristic values and process parameters of gas spark ignition engines

Characteristic values	• Electrical output up to > 1 MW, rarely below 100 kW • Electrical efficiencies 34–42% (for rated electrical outputs > 300 kW) • Service life: approx. 60,000 operating hours • Can be used with a methane concentration of approx. 45% or higher
Suitability	• Essentially any biogas plant, but economic use more likely in larger plants
Advantages	+ Specially designed to run on gas + Emission standards very broadly met (it is possible that formaldehyde emission limits may be exceeded, however) + Low maintenance + Overall efficiency higher than with pilot ignition gas engines
Disadvantages	- Slightly higher initial capital expenditure compared with pilot ignition gas engines - Higher costs because produced in small numbers - Lower electrical efficiency than pilot ignition gas engines in the lower power output range
Special features	• An emergency cooler must be installed in order to prevent overheating when heat demand is low • Power regulation as a function of gas quality is possible and recommended
Designs	• As a stand-alone unit inside a building or as a compact containerised unit
Maintenance	• See section on maintenance

Table 6.9: Characteristic values and process parameters of pilot ignition gas engines

Characteristic values	• 2–5% ignition oil concentration for combustion • Electrical output up to approx. 340 kW • Service life: approx. 35,000 operating hours • Electrical efficiencies 30-44% (efficiencies of around 30% for small plants only)
Suitability	• Essentially any biogas plant, but economic use more likely in smaller plants
Advantages	+ Cost-effective use of standard engines + Higher electrical efficiency compared with gas spark ignition engines in the lower power output range
Disadvantages	- Coking of injection nozzles results in higher exhaust gas emissions (NO_X) and more frequent maintenance - Engines not specifically developed for biogas - Overall efficiency lower than with gas spark ignition engines - An additional fuel (ignition oil) is required - Pollutant emissions often exceed the standards specified in TA Luft - Short service life
Special features	• An emergency cooler must be installed in order to prevent overheating when heat demand is low • Power regulation as a function of gas quality is possible and recommended
Designs	• As a stand-alone unit inside a building or as a compact containerised unit
Maintenance	• See section on maintenance

Table 6.10: Emission standards specified by TA Luft of 30 July 2002 for combustion engine plants according to No. 1.4 (including 1.1 and 1.2), 4th Implementing Regulation of the Federal German Pollution Control Act (4. BImSchV) [6-16]

Pollutant	Unit	Gas spark ignition engines		Pilot ignition gas engines	
		Rated thermal input			
		< 3 MW	? 3 MW	< 3 MW	? 3 MW
Carbon monoxide	mg/m^3	1,000	650	2,000	650
Nitrogen oxide	mg/m^3	500	500	1,000	500
Sulphur dioxide and sulphur trioxide given as sulphur dioxide	mg/m^3	350	350	350	350
Total particulates	mg/m^3	20	20	20	20
Organic substances: formaldehyde	mg/m^3	60	20	60	60

are to be used as a source of information when checks are performed to determine compliance with the obligations on operators. There is, for example, an obligation to minimise those harmful environmental impacts that are unavoidable using state of the art technology, although the licensing authorities deal with this in different ways [6-33]. The emission standards specified in TA Luft distinguish between pilot ignition gas engines and gas spark ignition engines. The required limits according to TA Luft of 30 July 2002 are listed in Table 6.10.

A supply of thoroughly treated fuel gas can help to minimise the pollutant concentrations in the exhaust gas. Sulphur dioxide, for example, results from the combustion of hydrogen sulphide (H_2S) contained in the biogas. If the concentrations of undesirable trace constituents in the biogas are low, the concentrations of their combustion products in the exhaust gas will also be low.

In order to minimise nitrogen oxide emissions, the engines are run in lean-burn mode. Thanks to lean burn it is possible to lower the combustion temperature and thus reduce the formation of nitrogen oxides.

Catalytic converters are not normally used with CHP units powered by biogas. The accompanying substances contained in the biogas, such as hydrogen sulphide, cause catalytic converters to be deactivated and irreparably damaged.

Lean-burn gas spark ignition engines normally have no problem complying with the emission standards demanded in TA Luft. Pilot ignition gas engines generally have poorer emission levels than gas spark ignition engines. Particularly the nitrogen oxide (NO_X) and carbon monoxide (CO) emissions can exceed the limits laid down in TA Luft in certain circumstances. Because of the ignition oil used for ignition of the engines, there are also soot particles contained in the exhaust gas [6-33], [6-7], [6-26]. The latest findings indicate that there are often problems complying with formaldehyde emissions [6-15]. Post-oxidation systems and activated carbon filters are available to ensure compliance with the emissions standards in TA Luft and EEG 2009 (40 mg/m^3), although so far the use of such equipment has not become widespread.

6.2.1.4 Generators

Either synchronous or aysnchronous (induction) generators are used in combined heat and power units. Because of high reactive current consumption, it makes sense to use asynchronous generators only in units with a rating lower than 100 kW_{el} [6-27]. Consequently, synchronous generators are normally used in biogas plants.

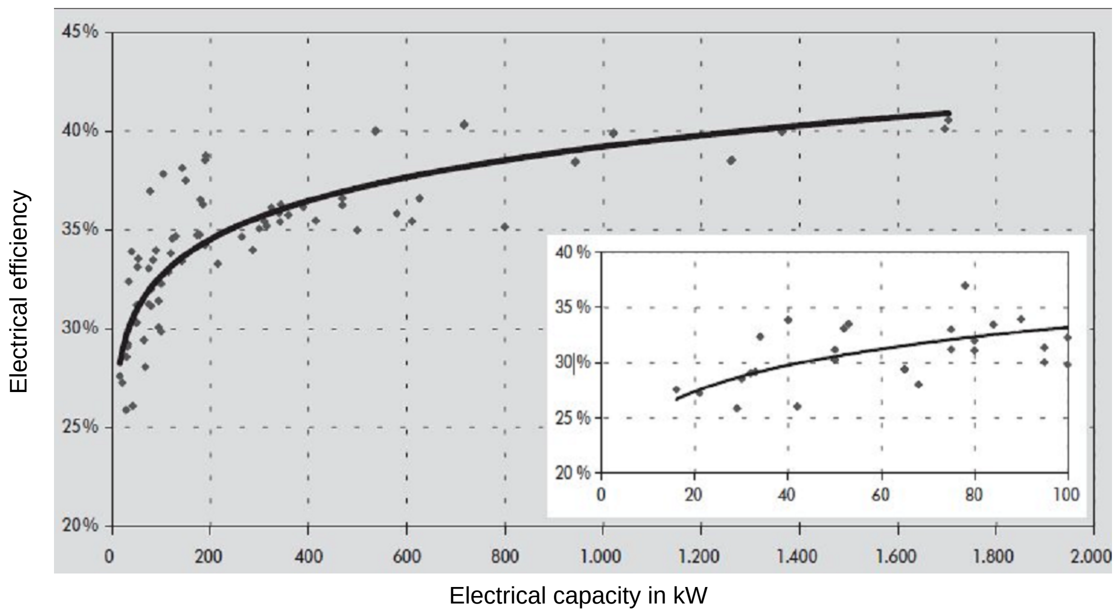

Figure 6.6: Electrical efficiency of biogas CHP units [6-41]

6.2.1.5 Electrical efficiencies and output

The efficiency of a combined heat and power unit is a measure of how efficiently the supplied energy is converted. The overall efficiency is made up of a combination of electrical and thermal efficiency, and normally lies between 80 and 90%. In the ideal case, therefore, 90% of the total rated thermal input can be used for energy conversion.

The rated thermal input is calculated as follows:

$$\dot{Q}_F = (\dot{v}_B \cdot H_i)$$

Equation 6-1: Q_F = rated thermal input [kW]; v_B = biogas flow rate [m³/h]; H_i = calorific value of the biogas [kWh/m³]

As a rule of thumb for gas spark ignition and pilot ignition gas engines it can be assumed that the electrical and thermal efficiency will each account for 50% of overall efficiency. The electrical efficiency is made up of the mechanical efficiency of the engine and the efficiency of the generator, and is obtained by multiplying the two efficiencies. An overview of the achievable efficiencies is shown in Figure 6.6.

The electrical efficiencies of CHP units powered by pilot ignition gas engines are between 30 and 43%. At least in the lower power output range they are higher than those of CHP units powered by gas spark ignition engines with the same electrical output. The efficiencies of CHP units powered by gas spark ignition engines are between 34 and 40%. The electrical efficiencies of both pilot ignition gas engines and gas spark ignition engines rise with increasing electrical output. As the efficiencies are calculated by CHP unit manufacturers under test bed conditions (continuous operation with natural gas), the figures obtained in real-world operation of a biogas plant are usually lower than the manufacturer's values. In particular it should be noted that in practice it is extremely rare to be able to run continuously at full load and that efficiencies in part-load operation are lower than at full load. This dependency is unit-specific and can be deduced from the respective technical data sheets.

A multiplicity of factors can influence the electrical efficiency, performance and noxious gas emissions of a CHP unit. In particular, not only engine components, such as spark plugs, engine oil, valves and pistons, but also air filters, gas filters and oil filters are subject to age-related wear. These wearing components should be replaced at regular intervals in order to prolong the service life of the CHP unit. The required maintenance intervals are normally specified by the CHP unit manufacturer. The way the CHP unit is set up, such as the lambda ratio, ignition timing and valve clearance, also has a substantial influence not only on the electrical efficiency and output, but also on the level of emissions of harmful gases. The performance of maintenance and adjustment operations is the responsibility of the plant operator. This work can either be carried out by the plant operator or outsourced through a maintenance contract with a service team from the CHP unit manufacturer or other service provider. In general terms it can be stated that, if the CHP unit is set up to within the range of the emission standards specified in TA Luft, this will have a considerable influence on the quality of combustion, electrical output and electrical efficiency [5-26].

6.2.1.6 Heat extraction

In order to utilise the heat produced during the generation of electricity, it is necessary to extract the heat using heat exchangers. In a CHP unit powered by an internal combustion engine, the heat is produced at various temperatures. The greatest quantity of heat can be obtained from the engine's cooling water system. The temperature level available here means that it can be used to provide heating energy or process energy. A heat distributor is shown in Figure 6.7. In most cases plate heat exchangers are used to extract the heat from the cooling water circuit [6-13]. The extracted heat is then distributed to the individual heating circuits via a distributor.

Figure 6.7: Heat distributor [MT-Energie GmbH]

The temperature of the exhaust gas is between about 460 and 550 °C. Stainless-steel exhaust gas heat exchangers, usually in the form of shell-and-tube heat exchangers, are used for extraction of waste heat from the exhaust gas [6-13]. Typically used heat-transfer media include steam at various pressures, hot water and thermal oil.

The plant's own heat requirements can be met very quickly with the waste heat from the CHP unit. As a rule it is only in winter that these requirements are high, whereas in summer the emergency cooler has to dissipate most of the excess heat, unless the heat can be utilised externally. In addition to the heat needed to heat the digester, which amounts to between 20 and 40% of the total heat produced, it is also possible, for example, to heat work spaces or residential premises. CHP units are fully compatible with standard heating systems and can therefore easily be connected to a heating circuit. In case the CHP unit breaks down, a heating boiler, which is often available anyway, should be kept in reserve for emergency operation.

Alongside other heat sinks on site (e.g. cowshed heating or milk cooling), supplying the heat to external offtakers beyond the boundaries of the farm can also prove economically successful. Given the rising substrate costs for renewable resources, it may be the case that selling the heat is the only way to make a plant profitable at all. This is assisted by the CHP bonus under the Renewable Energy Sources Act (EEG). According to this, existing facilities receive 2 cents per kWh of electricity generated if the heat is utilised in accordance with the provisions of EEG 2004. For new facilities this bonus rises to 3 cents per kWh if the heat is utilised in line with the Positive List of EEG 2009. The same applies to existing facilities that satisfy EEG 2009.

If there is a good market for the heat, it may also make sense to save heat by improving the insulation of the digester or by making the heat input into the digester more efficient. If the intention is to sell heat, however, it should be remembered that in some cases continuity of heat supply is required, which often has to cover maintenance intervals and plant downtimes. Potential users of the heat will be nearby commercial or municipal facilities (horticultural enterprises, fish farms, wood drying plants, etc.) or residential buildings. There is particular potential for heat utilisation in upgrading and drying processes which require a large input of thermal energy. Another alternative is combined cooling, heat and power (see 6.2.5.2).

6.2.1.7 Gas control train

For a gas engine to be able to make efficient use of biogas, the gas has to meet certain requirements in terms of its physical properties. In particular these include the pressure at which the biogas is supplied to the gas engine (usually 100 mbar) and a defined flow rate. If these parameters do not meet the requirements, for example if insufficient gas is released in the digester, the engines are operated at part load or shut down. In order to keep the settings as constant as possible and to meet the safety requirements, a gas control train is installed directly upstream of the CHP unit.

The gas control train, including the entire gas pipeline, should be approved in accordance with DGVW guidelines (German Technical and Scientific Association for Gas and Water). All gas pipes must be identified by either yellow colour or yellow arrows. The control train must contain two automatically closing valves (solenoid valves), a shutoff valve outside the installation room, a flame arrester and a vacuum monitor. It makes sense to integrate a gas meter into the gas control train (to measure the gas quantity) and a fine filter to remove particles from the biogas. If necessary, a compressor is also installed in the gas train. An example of a gas control train is shown in Figure 6.8.

When installing the gas pipes it is particularly important to include condensate drains, since even small quantities of condensate can cause blockage of the gas pipe because of the low gas pressures.

Figure 6.8: CHP unit with gas control train [DBFZ]

6.2.1.8 Operation, maintenance and installation sites

Compliance with certain general conditions is essential when biogas is used in a combined heat and power plant. In addition to actual running of the plant, it is also necessary to observe prescribed maintenance intervals and ensure that the installation site of the CHP unit meets certain requirements.

Operation

Thanks to various control and monitoring facilities, it is usual for a CHP unit to run largely automatically. To ensure that operation of the CHP unit can be assessed, the following data should be recorded in an operating log in order to establish trends:

- Number of operating hours
- Number of starts
- Engine cooling water temperature
- Flow and return temperature of the heating water
- Cooling water pressure
- Oil pressure
- Exhaust gas temperature
- Exhaust gas back pressure
- Fuel consumption
- Generated output (thermal and electrical).

As a rule, the data can be recorded and documented via the CHP unit's control system. It is often possible to link the CHP control system with the control loops of the biogas plant and to exchange data with a central control system or to transmit data over the internet, which allows remote diagnostics to be performed by the manufacturer. A daily tour of inspection and visual check of the plant should still be performed, however, despite all the electronic monitoring facilities. In CHP units with pilot ignition gas engines, the consumption of ignition oil should also be measured in addition to the quantity of gas consumed.

To be able to provide information about the thermal efficiency of the CHP unit, the amount of heat produced should be measured by heat meters, as well as the amount of electricity produced. This also makes it possible to provide relatively precise information about the amount of process heat required or about the amount of heat required by other loads (such as cowsheds, etc.) connected to the CHP unit's heating circuit.

To ensure that the engines have an adequate supply of gas, an appropriate flow pressure must be guaranteed before the gas enters the gas control train. Unless the biogas is stored under pressure, the pressure of the gas must be raised with the aid of gas compressors.

The lubricating oil has a big part to play in the safe and reliable operation of an engine. The lubricating oil neutralises the acids arising in the engine. Because of ageing, contamination, nitration and a reduction in its neutralisation capacity, the lubricating oil must be replaced at regular intervals, depending on the type of engine, type of oil and number of operating hours. The oil must be changed at regular intervals, and an oil sample should be taken before each oil change. The oil sample can be examined in a specialised laboratory. The laboratory results can be used to help decide on the length of the interval between oil changes and to provide information about engine wear [6-12]. These tasks are often covered by maintenance contracts. To lengthen the intervals between oil changes, the quantity of oil used is often increased by fitting enlarged oil sumps, which are available from many manufacturers.

Maintenance

If a CHP unit is to be operated with biogas, it is essential to keep to the specified maintenance intervals. This also includes preventive maintenance such as oil changes and the replacement of wearing parts. Inadequate maintenance and servicing can cause damage to the CHP unit and therefore give rise to considerable costs [6-12], [6-23].

Every CHP unit manufacturer provides an inspection and maintenance schedule. These schedules indicate what work needs to be carried out at what intervals to keep the equipment in good working order. The time allowed between the various maintenance measures depends on factors such as the type of engine. Training courses offered by CHP manufacturers enable plant operators to perform some of the work themselves [6-12].

In addition to maintenance schedules, manufacturers also offer service contracts. The plant operator should clarify the details of service contracts before purchasing the CHP unit, paying particular attention to the following points:

- which work is performed by the operator;
- what form of service contract is agreed;
- who supplies the operating materials;
- what is the duration of the contract;
- whether the contract includes a major maintenance inspection;
- how unexpected problems will be dealt with.

Precisely which services are included in a service contract will depend, among other things, on what work can be performed by the operator in-house. The VDMA Power Systems Association has drawn up a specification and a sample contract for maintenance and service contracts. This specification formed the basis for VDI Guideline 4680 'Combined heat and power systems (CHPS) – Principles for the drafting of service contracts'. Information about the contents and structure of such contracts can be obtained from there [6-2]. According to VDMA it is possible to define various forms of service contract.

Figure 6.9: Installation of a CHP unit inside a building and in a CHP container [Seva Energie AG]

An **inspection contract** covers all work needed to establish and assess the actual condition of the plant being inspected. Remuneration may be in the form of a lump sum payment or is determined according to actual expense; it also needs to be clarified whether inspections are performed once only or at regular intervals.

A **preventive-maintenance contract** covers the measures required to maintain the desired condition of the plant. The work to be performed should be described in a list, which becomes part of the contract by reference. The work may be carried out periodically or depending on the condition of the plant. The parties to the contract may agree on remuneration according to actual expense or as a lump sum. Depending on the nature of the contractual agreement, the correction of faults that cannot be eliminated by the operator may also be included in the scope of services.

A **corrective-maintenance contract** covers all the measures required to restore the desired condition. The work to be performed will depend on the circumstances of the individual case. Remuneration is normally determined according to actual expense [6-1].

A **maintenance contract**, also referred to as a full maintenance contract, covers the measures needed to maintain safe and reliable operation (maintenance and repair work, installation of replacement parts, and consumables apart from fuel). A general overhaul is also included, on account of the length of the contract (normally 10 years). This contract is most closely equivalent to a guarantee. Remuneration is usually in the form of a lump sum payment [6-1].

The average service life of a pilot ignition gas engine is 35,000 operating hours [6-28] [6-29], which, at 8,000 operating hours per year, is equivalent to about four-and-a-half years. After that a general overhaul of the engine is required. This usually involves replacing the entire engine, because a general overhaul is not worthwhile in view of the low price of engines. The average service life of a gas spark ignition engine can be assumed to be 60,000 operating hours or roughly seven-and-a-half years. Again, after this a general overhaul of the engine will be due. In this case almost all the components will be replaced apart from the engine block and crankshaft. After a general overhaul the engine can be expected to run for the same length of time again [6-2]. Service life is greatly dependent on, among other things, how well the engine is maintained and is therefore likely to vary considerably.

Installation sites

A combined heat and power unit should always be installed inside a suitable building. To reduce noise emissions, the building should be clad with sound insulation material and the CHP unit itself should be fitted with an acoustic hood. As well as allowing sufficient space to perform maintenance work, it is essential to ensure that there is an adequate supply of air to be able to meet the air demand of the engines. This may make it necessary to use inlet-air and exhaust-air fans. Further details of the requirements to be met by installation sites for CHP units can be taken from the safety rules for agricultural biogas plants.

CHP units installed in soundproofed containers are available for installation outdoors. These containers normally satisfy the requirements for installation sites specified by CHP manufacturers. Another advantage of containerised units is that they are fully assembled on the CHP manufacturer's premises, and subsequently tested. The time needed on site, from installation to commissioning, can then be reduced to one or two days. Examples of CHP unit installations are shown in Figure 6.9.

6.2.2 Stirling engines

Stirling engines are a type of hot-gas or expansion engine. In this case, unlike in an internal combustion engine, the piston is displaced not by the expansion of combustion gases from combustion inside the engine, but by the expansion of an enclosed gas, which is caused to expand by the supply of energy or heat from an external energy source. This separation of the source of energy or heat from the actual generation of power in a Stirling engine means that the necessary heat can be made available from a variety of energy sources, such as a gas burner fuelled by biogas.

The fundamental principle underlying the Stirling engine is that a gas performs a certain expansion work when there is a change in temperature. If this working gas is moved back and forth between a space with a constantly high temperature and a space with a constantly low temperature, then continuous operation of the engine is possible. The working gas is thus circulated. The operating principle is shown in Figure 6.10.

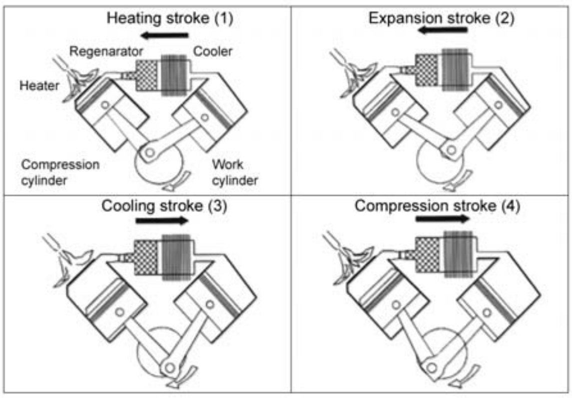

Figure 6.10: Operating principle of a Stirling engine from [6-14] according to [6-21]

Thanks to continuous combustion, Stirling engines have low pollutant emissions and low noise emissions, as well as low maintenance requirements. Given the low stresses on the components and the closed gas circuit, the operator is entitled to hope that maintenance costs will be low. In comparison with a conventional gas spark ignition engine, the electrical efficiency is lower, lying between 24 and 28%. The power output from a Stirling engine is mostly in the range below 100 kW_{el} [6-34].

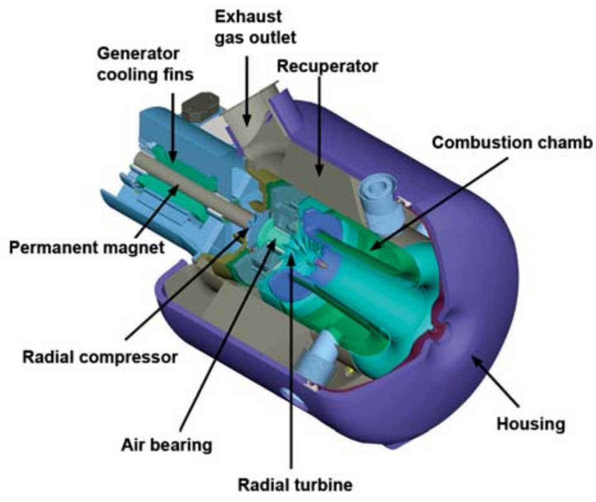

Figure 6.11: Construction of a gas microturbine [Energietechnologie GmbH]

Because combustion takes place externally there are low requirements concerning the quality of the biogas, which makes it possible to use gas with a low methane content [6-14]. The biggest advantage of a Stirling engine over a conventional biogas-fuelled internal combustion engine could be the fact that prior purification of the biogas is not necessary. One disadvantage is the inertia in case of a change of load, although this is less important in stationary installations, such as combined heat and power units, than in motor vehicles, for example.

Natural-gas-powered Stirling engines are available on the market in very low power output classes. However, various additional technical developments will be needed before they can be used competitively in biogas technology. A Stirling engine can be used as a CHP unit in the same way as a pilot ignition gas engine or gas spark ignition engine. At present, though, there are still only a few pilot projects in Germany.

6.2.3 Gas microturbines

A gas microturbine is a small, high-speed gas turbine with low combustion chamber temperatures and pressures in the lower electrical output range up to 200 kW_{el}. There are currently a number of different manufacturers of gas microturbines in the USA and Europe. For improved efficiency, and in contrast to a 'normal' gas turbine, a gas microturbine has a recuperator in which the combustion air is preheated. The construction of a gas microturbine is shown in Figure 6.11.

In a gas turbine, ambient air is sucked in and compressed by a compressor. The air enters a combustion chamber, where biogas is added and combustion takes place. The resultant increase in temperature causes an expansion in volume. The hot gases pass into a turbine, where they expand. This releases considerably more power than is needed to drive the compressor. The energy that is not required to drive the compressor is used to drive a generator to produce electricity.

At a speed of approximately 96,000 rpm a high-frequency alternating current is generated, which is made available via power electronics for feed-in to the electricity grid. If biogas is to be used to power a gas microturbine, certain changes need to be made compared to operation with natural gas, for example to the combustion chamber and fuel nozzles. [6-8]. The sound emissions from a gas microturbine are in a high frequency range and can easily be insulated.

As the biogas has to be injected into the combustion chamber of the gas microturbine, where the pressure may be several bar, the gas pressure must be increased. Apart from the pressure in the combustion chamber, it is also necessary to take account of pressure losses in the gas pipe, valves and burners relating to fluid flow and mass flow, which means that the pressure increase can be up to 6 bar atmospheric pressure. For this purpose, a compressor is installed upstream of the gas microturbine on the fuel side.

Undesirable attendant substances in the biogas (especially water and siloxanes) can damage the gas microturbine, which is why the gas needs to be dried and filtered (if the siloxane concentration exceeds 10 mg/m^3 CH_4). Gas microturbines have a higher tolerance to sulphur than gas engines. They can run on biogas with a methane concentration of between 35 and 100% [6-7], [6-8].

Thanks to continuous combustion with high excess air levels and low combustion chamber pressures, gas microturbines have considerably lower exhaust gas emissions than engines. This enables the exhaust gases to be utilised in novel ways, such as for direct fodder drying or CO_2 fertilisation of plants cultivated under glass. The waste heat is available at a relatively high temperature level, and all of it is transported in the exhaust gases. This makes it cheaper and technically easier to make use of the heat than in the case of an internal combustion engine [6-8], [6-39], [6-37].

Maintenance intervals are significantly longer than for engines, at least in the case of gas microturbines powered by natural gas. The manufacturers quote a maintenance interval of 8,000 hours, with a service life of around 80,000 hours. A general overhaul is scheduled after about 40,000 hours, which includes replacement of the hot gas section.

A disadvantage of the gas microturbine is its relatively low electrical efficiency, at just under 30%. However, this rather low figure in comparison with a conventional biogas engine is counterbalanced by good part-load behaviour (50-100%) and constant efficiencies between maintenance intervals. Investment costs are around 15 to 20% higher than those of engine-based biogas utilisation concepts of equivalent output [6-39]. It is anticipated that costs will be reduced, however, once gas microturbines are more widely available on the market. Financial support is provided through EEG 2009, which grants a technology bonus of 1 ct/kWh_{el} for the use of gas microturbines. Trials are currently being undertaken with biogas-powered gas microturbines, although their practical relevance has not yet been proven.

6.2.4 Fuel cells

Fuel cells work in a fundamentally different way from conventional methods of generating energy from biogas. In this case, chemical energy is converted directly into electricity. Fuel cells guarantee high electrical efficiencies of up to 50% while being almost emissions-free in operation. Good levels of efficiency are achievable also in part-load operation.

The principle of the fuel cell can be compared to the reverse of the electrolysis of water. In electrolysis, water molecules are split into hydrogen (H_2) and oxygen (O_2) when electrical energy is supplied. In a fuel cell, on the other hand, H_2 and O_2 react to form water (H_2O), releasing electrical energy and heat in the process. For this electrochemical reaction, therefore, a fuel cell requires hydrogen and oxygen as 'fuel' [6-17]. The construction of a fuel cell is essentially always the same. The cell itself consists of two gas-permeable plates (anode and cathode), which are separated by an electrolyte. Various substances are used as the electrolyte, depending on the type of fuel cell. An example of a fuel cell illustrating the operating principle is shown in Figure 6.12.

Biogas always has to be conditioned before it can be used in a fuel cell. It is particularly important to remove sulphur, using the methods described in Section 6.1.1. Reforming of biogas converts methane into hydrogen. This involves different stages for the various types of fuel cell. These stages are described in detail in [6-31]. The various types of fuel cell are named after the type of electrolyte used. They can be divided into low-temperature (AFC, PEMFC, PAFC, DMFC) and high-temperature fuel cells (MCFC, SOFC). Which cell is best suited for a particular application depends on how the heat is utilised as well as on the available power output classes.

The polymer electrolyte membrane (PEM) fuel cell is a promising option for use in small biogas plants. Its operating temperature is 80 °C, which means that the heat can be fed directly into an existing hot water system. From the nature of the electrolyte it can be assumed that a PEM will have a long useful life, although it is highly sensitive to impurities in the fuel gas. At present, removal of the carbon monoxide produced during reforming is still seen as a critical problem.

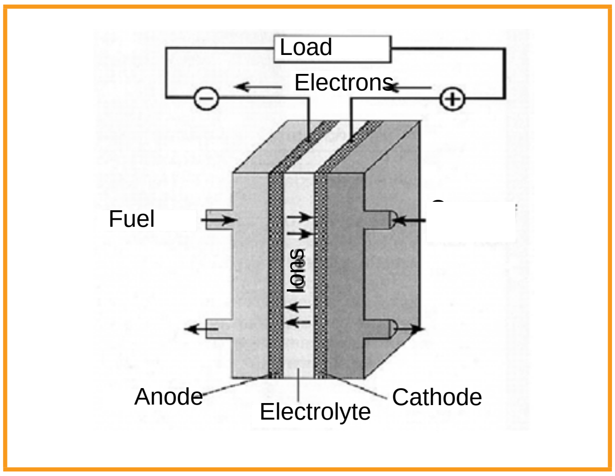

Figure 6.12: Operating principle of a fuel cell [vTI]

The furthest developed type of cell is the PAFC (phosphoric acid fuel cell). It is the most commonly used worldwide in combination with natural gas, and is presently the only commercially available fuel cell that has achieved up to 80,000 operating hours in practical trials [6-31]. There are currently PAFC cells available for use with biogas that cover the 100-200 kW_{el} power output range. Electrical efficiencies of up to 40% are feasible. The PAFC is less sensitive to carbon dioxide and carbon monoxide.

The MCFC (molten carbonate fuel cell) uses molten carbonate as electrolyte; it is insensitive to carbon monoxide and will tolerate carbon dioxide up to 40% by volume. Because of its working temperature of 600-700 °C, reforming can take place inside the cell. The waste heat can be put to further use in downstream turbines, for example. MCFC systems can achieve electrical efficiencies of up to 50% for a power output range of 40–300 kW_{el}. They are currently in the process of being introduced onto the market [6-31].

Another type of high-temperature fuel cell is the SOFC (solid oxide fuel cell). Operating at temperatures between 600 and 1,000 °C, it has high electrical efficiencies (up to 50%). Once again, reforming of methane to produce hydrogen can take place inside the cell. Its sensitivity to sulphur is low, which is an advantage when it comes to utilising biogas. So far, however, biogas applications are still at the research or pilot project stage. It is conceivable that SOFCs could be used in small-scale systems for micro biogas grids.

Manufacturers currently favour the PEMFC, which is in competition with the SOFC in low power output ranges (the SOFC has higher efficiencies but also higher costs) [6-31]. To date, however, it is the PAFC that has achieved market domination.

At present the investment costs for all types of fuel cell are still very high, and far removed from those of engine-powered CHP units. According to [6-31], the cost of a PEMFC is between €4,000 and 6,000/kW. The goal is between €1,000 and 1,500/kW. Various pilot projects are investigating the potential downward trend in investment costs and to what extent it is possible to eliminate those technical problems that still exist, particularly with respect to the utilisation of biogas.

6.2.5 Utilisation of waste heat in power-led CHP units

In the majority of cases the command variable for a CHP unit fuelled by natural gas or biomethane is the heat demand. This means that electric power can be exported without restriction, while the CHP unit is run to meet the demand for heat. The purpose of a heat-led CHP unit is in most cases to meet the base load of a client's heat demand (70–80% of annual demand), with peak demand being covered by additional boilers. In contrast, CHP is referred to as being power-led when the load curves of the CHP unit are defined with reference to the power demand. This may be the case if no power is fed into the grid or if the power demand is relatively constant. Large facilities or industrial sites with sufficient heat sinks are ideal for such an arrangement. In order to be able to achieve high running times, heat stores should be available and only the base load should be met. Facilities are often equipped with a load management system. This means that the CHP unit is able to switch between the two utilisation options as the need arises, which may be advantageous in housing schemes or hospitals, for example.

In practice the majority of biogas plants with distributed power generation are power-led, where the amount of power that is produced is based on the maximum amount that can be fed into the grid. This is limited by only two factors: the quantity of gas available and the size of the CHP unit. An overview of the economic efficiency of possible heat utilisation concepts is given in Section 8.4.

A third mode of operation with potential for the future, but which is not examined in greater detail here, is grid-led utilisation. This involves specifying an output level for several plants from a central location (virtual power plant). The fundamental choice between the two modes of operation is primarily determined by economic criteria.

6.2.5.1 Supply and distribution of heat (group heating schemes)

A crucial factor with regard to the economic operation of a biogas plant with on-site power generation is the sale of the heat produced during power generation. In rural areas in particular, a useful option is to sell the heat to nearby residents. In such cases, it could make sense to install group heating schemes (local heating networks) to sell the heat within a certain area. The network is made up of a twin run of insulated steel or plastic pipes that carry water at 90 °C (flow) and 70 °C (return). The heat is transferred from the biogas plant to the network via heat exchangers. Transfer stations and heat meters are installed in the individual buildings. The pipes of the local heating network should be protected by a leak detection system and be laid at sufficient depth (1 m) to withstand traffic loading and low temperatures. Attention should also be paid to the following points:

- Timely pre-project planning and conceptual design
- A high level of minimum heat consumption
- A sufficient number of residential units connected (at least 40)
- The greatest possible density of connected residential units within the given area.

The advantage for the heat offtakers who are connected to the network is that they are independent of the big energy markets. Consequently, they have high security of supply and ultimately a reduction in energy costs. So far this form of heat marketing has been implemented in a number of localities known as 'bioenergy villages' (for example Jühnde, Freiamt and Wolpertshausen). The lengths of the pipelines vary between 4 and 8 km. The economic efficiency of group heating schemes is described in more detail in Section 8.4.3.

6.2.5.2 Refrigeration

Another option for utilising the heat arising from biogas combustion is to convert the heat into cold. This is done using what is called the sorption method, which is differentiated according to adsorption and absorption refrigeration. The method described here, because of its greater relevance, is the absorption method, i.e. an absorption refrigerator, which is essentially familiar from old domestic refrigerators. The principle of the process is shown in Figure 6.13.

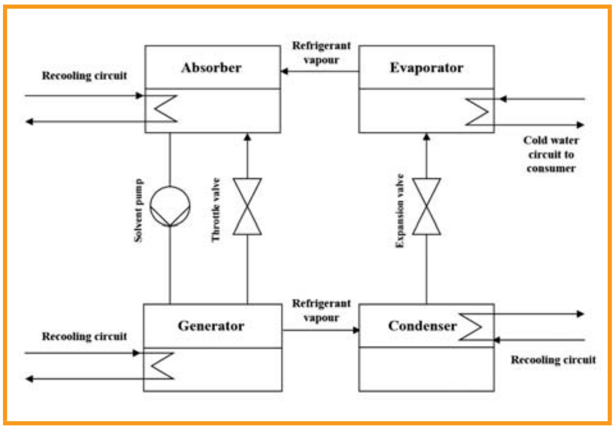

Figure 6.13: Functional diagram of an absorption refrigerator

An example of such a unit in use at a biogas plant is shown in Figure 6.14.

Figure 6.14: Example of an absorption refrigerator at a biogas plant [DBFZ]

A pair of working fluids, comprising a refrigerant and a solvent, is used to produce the refrigeration effect. The solvent absorbs a refrigerant and is subsequently separated from it again. The pair of working fluids can be either water (refrigerant) and lithium bromide (solvent) for a temperature range of 6/12 °C or ammonia (refrigerant) and water (solvent) for a temperature range down to -60 °C.

The solvent and refrigerant are separated from each other in the generator. For this, the solution needs to be heated, for which purpose the heat from the CHP unit is used. The refrigerant evaporates first, because it has a lower boiling point, and enters the condenser. The solvent, now with only little refrigerant, passes into the absorber. In the condenser the refrigerant is cooled, and consequently liquefied. In an expansion valve it is subsequently expanded to the evaporation pressure appropriate to the required temperature. The refrigerant is then evaporated in the evaporator, absorbing heat in the process. This is where the actual cooling takes place in the refrigeration cycle, and is the point at which the loads are connected. The resulting refrigerant vapour flows to the absorber. The refrigerant is absorbed by the solvent in the absorber, thus completing the cycle [6-13], [6-38].

As the only moving part in the system is the solvent pump, there is very little wear and consequently little maintenance is needed. Another advantage of absorption refrigeration units is their low electricity consumption compared with compression refrigeration systems, although the latter can also produce lower temperatures. The method is used in a variety of agricultural applications today, such as for cooling milk or air conditioning in cowsheds.

6.2.5.3 Concepts for the generation of electricity from waste heat

The organic Rankine cycle (ORC) is a process by which some of the excess waste heat from a CHP unit, even at low temperatures, can be converted into electrical energy. The principle of this technology is based on the steam cycle (see [6-14]), except that in this case it is not water that is used as the working medium but substances that boil and condense at low temperatures. The process was first used for power generation in geothermal applications, where it has been in successful use for many years. Trials are currently underway with environmentally safe substances (silicone oil) as the working medium. These substances are meant to replace the ones previously available on the market, which are either highly flammable (e.g. toluene, pentane or propane) or harmful to the environment (CFCs) [6-14]. Although the ORC process has often been used in combination with wood-fired power plants, use of this technology in combination with the combustion of biogas in engine-based power plants is still at the development stage.

It is estimated that additional power amounting to 70–100 $kW_{el.}$ (7-10%) can be obtained from a CHP unit rated at 1 $MW_{el.}$ with the aid of an ORC process [6-28].

According to [6-19], it has so far been possible to develop an ORC prototype with a design rating of 100 kW_{el} operating at an efficiency of 18.3%. In the meantime a small number of biogas plants with downstream ORC technology have commenced operation.

As an alternative to ORC technology there are developments that connect an additional generator directly to the exhaust gas turbine, thereby generating additional electric power and improving the efficiency of the engine.

6.3 Injection of gas into a grid

6.3.1 Injection into the natural gas grid

In Germany, biomethane is injected into a well-developed natural gas grid. There are large-scale natural gas transmission systems in place in both western and eastern Germany. These allow a nationwide supply to the population as well as the offtake of biomethane. The total length of the grid is around 375,000 km [6-5]. Most of the natural gas is imported from other European countries (85%). The main suppliers are Russia (35%), Norway (27%) and Denmark (19%) [6-10]. Because the supplies originate from different places, five different natural gas grids have emerged in Germany. These differ in terms of the quality of gas they carry (H and L gas grids).

Treated biogas can be injected into various types of grid at different pressure levels. A distinction is drawn between low-pressure grids (up to 100 mbar), medium-pressure grids (100 mbar to 1 bar) and high-pressure grids (1 to 120 bar). It is also common to differentiate between four supply levels: international long-distance transmission grid, supra-regional transmission grid, regional transmission grid and regional distribution network [6-5]. In order to optimise the costs of gas supply, the output pressure from the treatment process should be adapted to the existing grid pressure so that the cost of subsequent compression can be kept to a minimum. Before the treated biogas can be fed in, its pressure needs to be raised to a level above that at the entry point to the transmission pipeline. Each entry point therefore has to have its own pressure control and measuring station to monitor the pressure level.

The statutory regulations governing the feed-in of biogas have recently been eased in various ways. The amendment of the Renewable Energy Sources Act (1 January 2009), in conjunction with GasNZV (gas network access ordinance) and GasNEV (ordinance on gas network tariffs), which were amended in 2008 and 2010, enabled economically and technically controversial issues to be settled in favour of the feed-in of biogas. Among other things it was determined that the investment costs of connection to the grid, i.e. in particular the gas pressure control and measurement system, compressors and connecting pipeline to the public natural gas grid, are to be shared in a ratio of 75 to 25 between grid operator and biogas infeeder where the biogas plant is up to ten kilometres away from the gas grid. In addition, the grid connection costs for the infeeder are limited to €250,000 for distances up to one kilometre. Furthermore, the ongoing operating costs are the responsibility of the grid operator. The most important innovation to arise from the first amendment in 2008 was that, in future, producers of biomethane will be granted priority for connection to the grid and the transmission of gas [6-11]. In low-flow areas of the grid (distribution network) or at times of low flow ('mild summer nights'), the quantity to be fed in may therefore be higher than the capacity that the network can accommodate, in which case the grid operator must compress the excess gas and feed it into the higher-level grid. Feed-in into high-pressure networks is not currently state of the art. Compressors of various designs for different flow rates are available on the market, however. More detailed information about the legal framework is given in Chapter 7.

The quality requirements that the injected biogas needs to meet are likewise subject to regulation; these requirements are documented in the relevant DVGW regulations. Code of Practice G 262 lays down instructions relating to the properties of gases from renewable sources; G 260 governs gas quality and G 685 the billing of injected biomethane. The infeeder is responsible for upgrading the biomethane to the qualities required in these regulations; fine adjustment (adjustment of the calorific value, odorisation, adjustment of pressure) is the task of the grid operator. This work should be carried out as precisely as possible so as to avoid the formation of mixed and oscillating zones.

If it is intended to feed the biogas into a grid rather than utilise it on site, essentially there would be no change to the configuration of the biogas plant apart from the omission of the CHP unit. In the absence of a CHP unit, consideration would have to be given to alternative means of providing process power and heat. Process power can be obtained from the electricity grid, while heating of the digester and whatever process heat that may be required for the processing technologies (e.g. amine scrubbing) could be provided from heating boilers, for example. Another option would be the parallel operation of a CHP unit, which can be designed to provide the required process energy. The remaining biogas would then be available for injection into the grid.

6.3.2 Feed-in to micro gas grids

A micro gas grid is a means of connecting a biogas plant to one or more gas utilisation facilities (satellite CHP units) through pipes. This is worth considering in cases where, although it is not possible to utilise all the biogas on site, there are heat offtakers available within an acceptable radius. In principle the procedure is similar to that of feeding biomethane into a natural gas grid. The difference is that the processing requirements are lower. As the energy content of the gas does not have to be changed, all that is required is gas drying and desulphurisation, using the methods described in 6.1.1 and 6.1.2. Another advantage is better utilisation of the heat, and the associated increase in overall efficiency.

Essentially there are two different variants of this approach: either operation exclusively with biogas, or admixture with natural gas, either continuously (to adjust the gas quality to a required level) or at certain times (to meet demand peaks). Preferred areas of application include self-contained units with uniform billing, municipal facilities, industrial processes and large agricultural enterprises.

The promotion of micro gas networks under the Renewable Energy Sources Act has not been possible to date because in this case the financial burden primarily results from the investment costs. Operating costs, on the other hand, are low. Promotion of investment is possible through the market incentive programme, however. This grants a subsidy of 30% for raw biogas pipelines with a minimum length of 300 m [6-6].

Several micro gas grids have been set up in Germany to date. Good examples include the biogas networks in Braunschweig and at the Eichhof agricultural centre. As all the bonuses specified in EEG 2009 remain applicable to a micro gas network, this form of biogas utilisation is an efficient option for biogas feed-in.

6.4 Fuel for motor vehicles

In Sweden and Switzerland biogas has for many years been used as a fuel for buses and trucks as well as in the private domain. A number of projects have also been conducted in Germany, although these have not yet been translated into widespread use. In addition to the biomethane filling station in Jameln, which sells pure biomethane, biomethane has been added to natural gas at over 70 filling stations since 2009 [6-3]. Up to now, this has tended to be done for political reasons (publicity) rather than on economic grounds.

If it is intended to use biogas as a fuel for vehicles, it has to be upgraded to an acceptable quality for use in the engines commonly found in today's motor vehicles. Apart from substances with a corrosive effect on the engine, such as hydrogen sulphide, it is also necessary to remove the carbon dioxide (CO_2) and water vapour from the biogas. As the available vehicles are mostly natural gas vehicles, it is advisable to upgrade the biogas to natural gas quality (cf. Section 6.3.1).

In principle gas-powered vehicles are available on the global market and are sold by all major motor vehicle manufacturers, although the range on offer in Germany is still limited. The available models can be one of two types: monovalent or bivalent. Monovalent vehicles are powered solely by gas, but have a small petrol tank for use in an emergency. In a bivalent vehicle the engine can be powered either by gas or by petrol, as required. Because of the considerable volume of uncompressed biogas, such vehicles do not have an appreciable range. For this reason the biogas is stored in pressurised gas tanks at approximately 200 bar either in the rear or on the floor of the vehicle.

Since June 2002 biofuels have been tax-exempt, which gives the necessary degree of planning certainty for building biogas filling stations. The cost of upgrading the biogas is similar to that needed for feed-in to a grid, to which must be added the extra expense of compressing the biomethane to reach the necessary pressure level.

6.5 Thermal use of biogas

Upgraded biogas can easily be combusted to supply heat. The burners used for this purpose are mostly all-gas appliances, which can be converted to burn various fuels. Unless the biogas has been upgraded to natural gas quality, the appliance must be adapted to burn biogas. If the appliance contains components made of non-ferrous heavy metal or low-alloy steels, the hydrogen sulphide in the biogas can be expected to cause corrosion. Consequently, either these metals have to be replaced or the biogas must be purified.

Two types of burner can be distinguished: atmospheric burners and forced-air burners. Atmospheric burners obtain their combustion air by natural aspiration from the ambient air. The required gas supply pressure is approximately 8 mbar, which can often be provided from the biogas plant. In a forced-air burner, the combustion air is supplied by a fan. The required supply pressure to the burner is at least 15 mbar. It may be necessary to use a gas compressor to obtain the necessary gas supply pressure [6-13].

The amendment of the Renewable Energies Heat Act increased the importance of utilising biogas to generate heat. The Act stipulates that the owner of a building constructed after 1 January 2009 must ensure that the heat generated for the building comes from a renewable energy source. However, in addition to being confined to new buildings (with the exception of Baden-Württemberg) the Act is restricted to heat from CHP plants in relation to the use of biogas.

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Source: Paterson (left), Schüsseler (FNR)

Legal and administrative framework

7

Plant operators are faced with a variety of legal issues relating to both the planning and operation of biogas plants. Before construction of the plant begins, they have to give serious thought to the grid connection, the nature of the contract and the statutory requirements that need to be met. When they are first elaborating the plant concept, operators have to weigh up various options against each other: the design of the plant, the choice of feedstocks, the technology to be employed and the way the heat will be utilised, all with due consideration for the remuneration rates and bonuses set out under the Renewable Energy Sources Act (EEG). Finally, once the plant is in operation the plant operator must comply with all relevant requirements under public law, operate the plant in line with the provisions of EEG and provide all the necessary statutory certifications.

7.1 Promotion of electricity from biomass

The Renewable Energy Sources Act (EEG) has a substantial role to play in promoting the operation of biogas plants in Germany.

One of the purposes of the Act, which was most recently amended on 1 January 2009, is to increase the proportion of electricity supplied from renewable energy sources to at least 30% by 2020 in the interests of climate change mitigation and protection of the environment. Distributed generation of power from biomass – which according to the Biomass Ordinance (BiomasseV) also includes biogas obtained from biomass – can make a crucial contribution to achievement of this purpose.

Under EEG the operator of a biogas plant is entitled to connect the plant to the public electricity grid and to feed the power generated at the plant into the grid. Plant operators enjoy privileges over conventional power generators not only in relation to their connection to the grid: they also receive a statutory feed-in tariff for the electricity that they supply to the grid, for a period of 20 years. The level of the tariff is determined partly by the size of the plant, the date when it was commissioned and the input materials. The various bonuses provided for under EEG 2009 have a particularly important part to play in calculation of the feed-in tariff.

7.1.1 The bonus system under EEG

The purpose of the bonuses provided for under EEG is to establish a sophisticated incentive system to ensure the conversion of biomass into electricity in an innovative and efficient way that is climate-friendly and environmentally sound. Particular support is therefore provided for the generation of electricity from renewable resources, such as energy crops. The NawaRo bonus, as it is referred to in German (NawaRo = 'nachwachsende Rohstoffe', or renewable resources), was introduced in 2004. It is sometimes referred to in English as the energy crop bonus. The intention on the part of the legislator was to target support at both the growing of energy crops and the utilisation of manure, in the interests of climate change mitigation. Several other provisions of EEG also take account of climate change, for example the bonus for operation in a combined heat and power installation (CHP bonus). According to the latter, a significantly higher tariff is paid to plant operators who put the waste heat arising from power generation to meaningful use and consequently avoid burning fossil fuels, which is associated with CO_2 emissions. Innovative technologies that promise more efficient generation of electricity in the medium or long term but are not yet competitive at the present time are given targeted support through the technology bonus.

7.2 Grid connection and electricity feed-in

In order to qualify for support under EEG, the plant operator must feed the electricity generated at the plant into the public power grid, and make it available to the power grid operator. This first of all requires a physical grid connection by which the plant is connected to the power grid.

7.2.1 Grid connection

When planning and building a biogas plant it is particularly important for the plant operator to contact the relevant grid operator at an early stage and to clarify all the modalities relating to connection to the grid. Firstly, therefore, the plant operator will need to inform the grid operator of the intention to build a biogas CHP unit at a specific location. The grid operator should also be notified of the anticipated installed electrical capacity.

Before work on the grid connection can begin, it will normally be necessary to perform a grid compatibility test. The purpose of the grid compatibility test is to establish whether, where and, if applicable, under what conditions feed-in to the grid is physically and technically possible, given the electrical capacity the plant operator intends to provide. In practice the grid compatibility test is usually performed by the grid operator, although the plant operator may also commission a third party to do the work. In the latter case the grid operator is obliged to forward all the data needed to perform the test to the plant operator.

The plant operator will generally endeavour to keep the cost of grid connection to a minimum, and to feed the electricity into the grid at the point nearest to the plant. This is also the standard case as provided for under EEG. However, the grid connection point, i.e. the point at which electricity is fed into the power grid, may also be further away in certain circumstances. Determining the statutory grid connection point is a matter of crucial importance when it comes to sharing the associated costs between the plant operator and the grid operator, and can therefore often give rise to legal disputes (for more details on determining the grid connection point see 7.2.1.1).

The grid may sometimes need to be optimised, upgraded or strengthened to allow the power being fed in at the grid connection point to be received and transported without difficulty. The Act refers to this as a capacity expansion. The plant operator can request the grid operator to carry out a capacity expansion immediately, in so far as this is economically reasonable, if such an expansion is necessary in order to cope with the electricity generated at the biogas CHP unit. If the grid operator does not meet the plant operator's request, the latter may be able to claim compensation (for details of capacity expansion see).

Once the plant operator and grid operator have agreed on the grid connection point, the plant operator should submit an application to make a firm reservation of grid connection capacity. Work can then begin on **establishing the grid connection** – even before construction of the plant commences. The plant operator often commissions the grid operator to do this, but can also arrange for the grid connection to be made by a specialist third party. The same applies to metering the electricity fed into the grid. The cost of measures to establish a grid connection is basically borne by the plant operator (but see also 7.2.1.2 with regard to who pays what).

The plant operator's entitlement to a grid connection derives directly from EEG. A grid connection contract is therefore not absolutely essential. It may make sense to enter into a grid connection contract, however, especially to clarify technical issues between the plant operator and the grid operator. The plant operator should have the contract checked by a lawyer before signing it.

7.2.1.1 Determination of grid connection point

The point at which the connection to the power grid is to be made is referred to in the Act as the grid connection point. According to EEG, the connection should generally be made at the point in the grid system that is technically suitable for receiving the electricity with regard to voltage level and is at the shortest linear distance from the biogas plant. However, if it is apparent that the grid connection could be made at a different, more distant point of another grid at a lower overall cost, the connection should be made at that point of the other grid. According to the amended EEG of 1 January 2009 it is still unclear whether this is also the case if connection is less expensive overall at a more distant point in the same grid.

When a cost comparison is being carried out it is necessary to take an overall view, in which it is initially immaterial whether the grid operator or the plant operator would have to bear the costs in the alternative options under consideration. Instead, the statutory grid connection point should be determined on the basis of a macroeconomic comparison. The decision on which subsequently required measures are to be paid for by the plant operator and which by the grid operator should not be taken until the next stage.

This principle can be illustrated with the aid of an example: plant operator A constructs a biogas plant with an electrical capacity of 300 kW in the immediate vicinity of his farm, and would like to connect the plant to the public power grid. The power line closest to the site of the combined heat and power unit (15 m away) is a low-voltage line. However, the voltage level of the low-voltage line means that it is technically unsuited to receiving the electricity. The nearest connection point to a medium-voltage grid therefore needs to be found. If, however, it would be more expensive to make the connection there – for example because of the cost of the grid upgrade that would be required – than at another medium-voltage grid further away, then the plant should be connected at the latter point. The question of how the costs will be shared is put to one side for the time being (for further details see 7.2.1.2).

The plant operator is at liberty, however, to choose a different grid connection point rather than the one established according to the principles outlined above. One particular case where this may make sense is if the plant operator is able to obtain a connection significantly faster, and thus begin feed-in sooner. In these circumstances the plant operator must cover the additional costs.

Ultimately, however, the grid operator has the right to make the final decision and can assign a definitive grid connection point. If the grid operator makes use of this right, though, he must meet the additional costs arising over and above those for connection at the statutory connection point, i.e. the nearest and economically most advantageous point.

Capacity expansion

If the electricity cannot be fed in at the statutory grid connection point because the capacity of the grid is inadequate, the plant operator can demand that the grid operator must optimise, strengthen or upgrade the grid without delay in line with the state of the art. This entitlement also applies even before a permit under building law or pollution control legislation has been obtained, or before a provisional official decision has been taken. However, it is necessary for planning of the plant to have reached an advanced stage. This is the case, for example, if orders for detailed plans have already been issued or production contracts are in place.

The grid operator does not have to begin the upgrading work unless and until the plant operator expressly requests that this be done.

7.2.1.2 Costs of grid connection and grid capacity expansion

With regard to the costs associated with connecting a biogas plant to the public power grid, the law distinguishes between the costs of connection to the grid and those of upgrading the grid. Accordingly, the plant operator bears the cost of connecting the plant to the grid, whereas the grid operator has to pay for optimising, strengthening and upgrading the grid. In practice it is often a matter of dispute whether a particular measure – such as laying a power line or constructing a transformer substation – should come under the category of grid connection or grid upgrading. The decisive factors are whether the measure is necessary for operation of the grid and who has or acquires ownership of the installed lines or other installation components. In individual cases this can give rise to difficult questions of differentiation. The plant operator should, however, always avoid assuming ownership of lines, transformers or other installations which he feels belong to the grid and do not form part of the equipment establishing the connection.

As the costs of construction work required for connecting the plant to the grid can vary considerably and are largely dependent on the grid connection point, it is apparent in this regard, too, that the choice of connection point is particularly important for the plant operator.

7.2.2 Feed-in management

Under EEG, operators of biogas plants or other EEG plants with an electrical capacity of over 100 kW are obliged to equip the biogas plant with certain technical devices in order to allow effective feed-in management by the grid operator. The purpose of feed-in management is to prevent overloading of the grid. To that end, the grid operator is entitled, in the circumstances set out in the law, to reduce the output from power generation plants with a capacity of over 100 kW or to disconnect them from the grid. In such cases, however, the grid operator must always take account of the priority granted to electricity from renewable energy sources and from combined heat and power generation over conventionally generated electricity. If there is a danger of grid overload, therefore, the grid operator must first regulate the output of conventional power generating plants.

In detail, the Act provides that biogas plants with a capacity of over 100 kW must be equipped with a technical or operational facility that enables the power being fed in to be reduced under remote control and that also measures the amount of power being fed in and makes this data available to the grid operator. Biogas plants that entered service before 1 January 2009 had to be suitably retrofitted by the end of 2010 at the latest.

If the grid operator reduces the output of a plant for a certain period of time, it must compensate the plant operator for the otherwise payable EEG remuneration as well as for any lost revenues from the sale of heat. For his part, however, the plant operator must allow any savings – especially saving of fuel costs – to be deducted.

7.2.3 Power feed-in and direct selling

A prerequisite for receipt of the EEG tariff is that the electricity must be fed into the public grid and made available to the grid operator. If the plant is connected to the plant operator's own network (e.g. a company network) or to a grid belonging to a third party, feed-in to the public grid can take place on a commercial and accounting basis.

Although the plant operator is at liberty to utilise some or all of the electricity he has generated to meet his own needs or to supply power to third parties with a direct connection to his plant, the plant operator will not receive any payment under EEG in either case.

Plant operators can also temporarily forego payment of the EEG tariff and can themselves engage in direct selling of the electricity they feed into the public power grid, either on the electricity wholesale market or directly to third parties. If the electricity is sold on an electricity bourse, it is sold without reference to its method of generation, in other words as 'grey electricity'. In addition, however, plant operators have the option of marketing the added ecological value of power generation from renewable energy sources in the form of green electricity certificates (e.g. RECs). In bilateral supply contracts it is also possible to consider selling the electricity directly as 'green electricity'. Direct selling does not make economic sense, though, unless the revenues from selling the electricity for the plant operator's own account are higher than those that could be earned from the EEG tariff.

If plant operators decide to sell their electricity directly, they must do so for entire calendar months. They may switch between the EEG tariff and direct selling on a month-by-month basis, but they must notify the grid operator of the switch before the start of the previous calendar month. For example, if a plant operator wishes to change to direct selling with effect from October 2010, he must inform the grid operator of this no later than 31 August 2010. If he then wishes to revert to the EEG tariff with effect from November 2010, he must declare this to the grid operator no later than 30 September 2010.

Plant operators are also at liberty to directly sell only a certain percentage of the electricity generated in a given calendar month, rather than all of it, and to continue to claim the EEG tariff for the remainder of the electricity. Also in this case, they must notify the grid operator of the percentage of electricity to be sold directly before the start of the previous calendar month, and they must verifiably keep to this percentage at all times. The percentage must be maintained for every quarter-hour of the month.

7.3 EEG tariffs

Entitlement to payment of the EEG tariff commences as soon as electricity generated exclusively from renewable energy sources begins to be fed into the public power grid. The entitlement applies to the plant operator, i.e. whoever uses the plant for the generation of power, irrespective of the ownership situation, and implies a claim against the operator of the power grid receiving the electricity.

7.3.1 Basis for determining payments

The following sections describe in detail how the level of payments is determined, and the period for which they are paid. An outline of the fundamental principles is followed by an examination of what is meant by the terms plant (or 'installation' as used in the Act) and commissioning, which are crucial for the level and duration of the payments. The final sections look more closely at the various bonuses payable under EEG for power generated from biogas.

7.3.1.1 Level of tariff payments

The level of the EEG tariff is determined by, among other things, the size of the plant, the date when it was commissioned and the energy source. In addition, the law includes a differentiated bonus system offering various incentives to use certain input materials, employ innovative technologies and make efficient use of heat.

When the level of payment is calculated, the first point to note is the size of the biogas plant: the higher the installed electrical capacity of the plant, the lower the payment for the generated power. The law thus takes account of the fact that the specific cost of each kilowatt-hour of electricity generated falls as the size of the plant increases. To compensate for this, smaller plants, which the legislator considers particularly worthy of promotion, receive a higher tariff.

As it differentiates according to the size of plant, EEG provides for a sliding scale of payments based on legally defined capacity thresholds. If the electrical capacity of the plant exceeds a certain threshold, when the payment is being calculated the power generated must be set into relation with the respective capacity thresholds. The average EEG tariff for electricity from a biogas plant is thus calculated from the average of the payments granted for each of the individual shares of capacity. This ensures that the average payment is reduced only slightly where output exceeds a certain threshold by an insignificant amount, and that operation of a biogas plant tailored to the specific location makes economic sense.

It is not the installed electrical capacity of the plant but its average annual output that determines how the power fed to the grid is allocated to the various shares of capacity. The average annual output is calculated by dividing the total amount of electricity fed into the grid in a calendar year by the total number of full hours in that calendar year – as a rule, therefore, by 8,760. A side-effect of this is that plants which have not generated any electricity for a certain period because of maintenance work, for example, will receive a higher average payment per kilowatt-hour than they would be entitled to if they had been in continuous full-load operation.

7.3.1.2 Duration of tariff payments

The entitlement to payment of the EEG tariff does not continue for an unlimited time; it is restricted to a period of 20 calendar years plus the remaining part of the year in which the biogas plant was commissioned. For example, if a plant is commissioned on 1 July 2010, the payment period begins on 1 July 2010 and ends on 31 December 2030. The commissioning date of a plant is the date it began operation, irrespective of the fuel it uses. If a plant is initially run on natural gas or fuel oil, for example, and is converted to biogas at a later date, the payment period begins on the date it commenced operation with natural gas or fuel oil.

The statutory payment period continues to run even if the plant operator sells the electricity directly. The law makes no provision for an extension of the statutory payment period. Nor can it be extended by significant additional capital investment, as, since 1 January 2009, EEG no longer allows the recommissioning of plants. Replacing the generator does not cause the restarting of the payment period, either.

After the statutory payment period has come to an end, the right to claim payment of the EEG tariff lapses. Although a plant operator remains entitled to feed his electricity into the grid, with priority over other suppliers, from that time onwards he has to make efforts to sell the electricity directly.

7.3.1.3 Degression

The tariff level payable for a plant in the year it was commissioned remains constant for the entire statutory payment period.

However, lower tariff rates apply to plants commissioned in later years. EEG provides for an annual reduction in the minimum feed-in tariff, with different degrees of reduction depending on the type of renewable energy source. This is meant to take account not only of the growing profitability of power generation from renewable energy sources as technology advances, but also of growth in the number of plants built, which will generally result in falling prices.

At 1%, the annual reduction for electricity from biogas – for both the basic tariff and also the bonuses – is at the lower end of the degression scale. Nonetheless it serves as an economic incentive for the plant operator to ensure that the biogas plant is commissioned before the end of the year under consideration. On the other hand, if a plant is commissioned just before the end of a calendar year, the economic advantage of the resultant avoidance of degression must be weighed against the economic disadvantage of what would be, overall, a significantly shorter guaranteed EEG payment period, because the remainder of the commissioning year is extremely short.

For example, the operator of a plant with a capacity of 150 kW that is commissioned on 31 December 2009 receives a basic tariff of 11.67 cents per kWh. If the plant is not commissioned until 1 January 2010, the tariff is only 11.55 cents per kWh. In the former case, however, the tariff is paid for a period of twenty years and just one day, whereas in the latter case it is paid for twenty years and 364 days. All in all, therefore, the total payment under EEG is higher, despite the slightly reduced tariff level. It should be borne in mind, though, that it is impossible to predict trends in electricity prices. It may be the case, for example, that direct selling will become more attractive than the EEG tariff within as little as ten years, in which case the advantage of a longer payment period would no longer apply.

7.3.2 Definitions of plant and commissioning date – correctly determining the level of payment

Both the definition of what a 'plant' is and also the commissioning date of the plant are crucially important for determining the relevant tariff rate in each individual case.

Table 7.1: Tariffs for biogas plants commissioned in 2011

	Plant output as defined in Section 18 para. 2 EEG	Tariffs in cents per kWh (commissioned in 2011)[a]
Basic tariff for electricity from biomass	up to 150 kW up to 500 kW up to 5 MW up to 20 MW	11.44 9.00 8.09 7.63
Air quality bonus	up to 500 kW	+0.98
NawaRo bonus	up to 500 kW up to 5 MW	+6.86 +3.92
Manure bonus	up to 150 kW up to 500 kW	+3.92 +0.98
Landscape maintenance bonus	up to 500 kW	+1.96
CHP bonus	up to 20 MW	+2.94
Technology bonus	up to 5 MW	+1.96/+0.98[b]

a. According to the explanatory memorandum to the Act, the tariffs specified in EEG are first added, then reduced by the 1% annual degression rate and finally rounded to two decimal places. In individual cases, therefore, the applicable tariff may differ from the total of the tariffs specified here.
b. The lower figure applies to gas processing plants with a maximum capacity of over 350 normal cubic metres up to a maximum of 700 normal cubic metres of processed raw gas per hour.

7.3.2.1 Plant as defined in EEG

EEG defines a 'plant' (referred to as 'installation' in the English translation of the Act) as any facility generating electricity from renewable energy sources, i.e. basically any biogas plant with a CHP unit. In contrast with the legal position prior to 2009, it is no longer necessary for the plant to be 'independently' capable of generating electricity from renewable energy sources. According to the explanatory memorandum to the Act, this is meant to introduce a broader definition of the term 'plant'.

Plant configurations in which more than just one CHP unit is connected to a biogas plant are not easy to categorise under the law. Many issues are disputed in this regard and have not yet been finally clarified, despite a recommendation from the EEG Clearing Agency issued on 1 July 2010 (Ref. 2009/12). The comments below are solely a reflection of the author's personal views, are not generally binding and are no substitute for legal advice on individual cases.

In the opinion of the author and contrary to recommendation 2009/12 from the EEG Clearing Agency, two or more CHP units operated at the location of a biogas plant and jointly using the same biogas production facilities (digester, digestate tank, etc.) are not each to be considered as a separate plant, if for no other reason than because of the now broader definition of what a plant is. Rather, they are part of a joint plant. According to this view, the question of whether the additional requirements in Section 19 para. 1 of EEG are met is irrelevant. Thus, the average plant output, which is crucial for determining the level of tariff payment, must be calculated on the basis of the total amount of electricity fed into the grid in a calendar year. In other words: to calculate the tariff, the outputs from the individual CHP units – which will, as a rule, be fed to the grid through a common line – are counted together as a single output. Consequently, assuming that the CHP units have similar operating hours, a biogas plant with one 300 kW CHP unit will receive the same feed-in tariff as a biogas plant with two 150 kW units.

A special case that can be singled out is that of **satellite CHP units**. These are additional CHP modules that are directly connected to the biogas generating plant via a raw biogas pipeline. If located at a sufficient distance from the CHP unit at the biogas generating plant, a satellite CHP unit can be assumed to be an independent plant. However, EEG does not contain any specific criteria defining the conditions under which a plant can be considered a legally independent entity. In practice, a distance of roughly 500 m has increasingly emerged as the standard for the key criterion of 'direct spatial proximity'. Beyond this distance, a satellite CHP unit should always be classed as an independent plant. This definition has no basis in the wording of the law, however, as was also expressly emphasised by the EEG Clearing Agency in its recommendation of 14 April 2009 (Ref. 2008/49). In the author's view, therefore, it will be necessary to obtain the opinion of an objective third party and to assess each individual case on its merits. The efficient use of heat, for example, suggests that the satellite CHP unit is independent from a legal standpoint.

The legal status of a satellite CHP unit should be clarified with the relevant grid operator before construction is begun.

7.3.2.2 Grouping of two or more plants

Under certain circumstances, two or more biogas plants can be considered as a single plant for the purpose of calculating the tariff, even though they are each classed as separate plants according to the definition of 'plant' explained above.

The aim of this provision is to prevent plants being set up in a configuration designed to take unfair advantage. The legislation seeks to prevent the macro-economically senseless splitting of a potentially larger biogas plant into two or more smaller biogas plants for the sake of optimising tariff payments. The background to this is that two or more small plants will receive a significantly higher payment than one big plant, on account of the sliding tariff rates (cf. 7.3.1.1).

EEG lays down clear legal conditions to determine whether two or more plants shall be classed as one. If all of these conditions are met, the plants are considered to constitute a single plant.

According to Section 19 para. 1 EEG, two or more independent biogas plants will be classed as a single plant for the purpose of calculating the tariff payments, regardless of the ownership situation, if the following conditions apply:

- they have been built on the same plot of land or in direct spatial proximity;
- they each generate electricity from biogas or biomass;
- the electricity generated in the individual biogas plants is remunerated in accordance with the provisions of EEG as a function of plant capacity;
- the individual biogas plants were commissioned within a period of twelve consecutive calendar months.

According to the wording of Section 19 para. 1 EEG, however, the grouping of two or more plants as a single plant serves the sole purpose of determining the tariff payable for the most recently commissioned generator. As a rule, the generator will be identical with the CHP unit.

Example: Where three plants are grouped from a legal standpoint, the entitlement to receipt of the tariff remains unchanged for the plant commissioned first even after the second plant is commissioned.

When the entitlement to the tariff is being determined for the second plant, however, if the statutory conditions are cumulatively met, then Section 19 para. 1 EEG will apply, and the two plants will thus be grouped.

Similarly, the entitlement to the tariff for the second biogas plant will also remain unchanged when the third plant is commissioned. When it comes to determining the tariff to be paid for the third biogas plant, if the statutory conditions are met, all three biogas plants will be classed as a single plant.

The effect of Section 19 para. 1 EEG applies to both the entitlement to the basic tariff and also the entitlement to all bonuses, the levels of which are likewise linked to certain capacity thresholds. This is the case with the air quality bonus, energy crop bonus, manure bonus, landscape management bonus and technology bonus.

7.3.2.3 Examples of individual plant configurations

A few illustrative examples in the following are meant to show what impact various plant configurations can have on the status of the plants and hence on the payment of tariffs. The assessment of the examples is purely a reflection of the personal opinions of the author of this section; it does not claim to be generally binding; nor can it act as a substitute for legal advice in individual instances.

Example 1: A biogas plant comprises a digester, a secondary digester, a digestate storage tank and two or more CHP units operated at the same site as the biogas plant.

In the author's view, this is just a single plant, irrespective of the number of CHP units or the date when they were commissioned. In the opinion of the EEG Clearing Agency, on the other hand, this will be the case only if the CHP units were commissioned within 12 consecutive months of each other (Section 19 para. 1 EEG).

Example 2: A biogas plant is connected by raw biogas pipelines to two CHP units located on the same site as the biogas plant and to a third unit located at a distance of 150 metres on a plot of land immediately adjacent to the biogas plant site. All of the CHP units were commissioned in 2009.

In this case, the two first-mentioned CHP units are classed as one plant, as in example 1. In terms of the law governing tariff payments, the third CHP unit should also be grouped with this plant, as it is not an independent plant in itself. There is insufficient spatial and functional separation from the biogas plant.

Example 3: A biogas plant is connected by raw biogas pipelines to two CHP units located on the same site as the biogas plant and to a third unit on a plot of land that is not immediately adjacent to the biogas plant site and is 800 metres away. The third CHP unit is located in a nearby village; the waste heat is used to heat residential buildings. All of the CHP units were commissioned in 2009.

In this case, too, the two first-mentioned CHP units are classed as one plant. However, in contrast with example 2, the third CHP unit is classed as an independent plant because of its spatial and functional separation from the biogas plant. In this case, therefore, there are two plants: the biogas plant with two CHP units, and the independent, third CHP unit. Grouping of all three installations into a single plant under Section 19 para. 1 EEG cannot apply, because the third CHP unit is not in 'direct spatial proximity' to the main plant.

Example 4: Ten biogas plants, each comprising a digester, a secondary digester, a digestate storage tank and a CHP unit of identical capacity, not connected to each other in any way, are located 20 metres apart on a piece of land parcelled out between the individual biogas plants. All of the biogas plants were commissioned in 2009.

In this case, it is true that each of the biogas plants is a complete, separate installation within the meaning of Section 3 No. 1 EEG. However, for the purposes of determining the tariff payment, the biogas plants are classed as one plant according to Section 19 para. 1 EEG because they are in direct spatial proximity to each other and were commissioned within a twelve-month period.

Section 19 para. 1 EEG also applies to plants that were commissioned before 2009. Especially those sites that can be described as plant parks, therefore, initially had to deal with considerable reductions in tariffs after 1 January 2009. Since the introduction of Section 66 para. 1a EEG, however, which was included in the Act on 1 January 2010, plants that were already operated as modular plants prior to 1 January 2009 are classed as separate plants, notwithstanding Section 19 para. 1 EEG. According to the explanatory memorandum to the Act, operators of such plants can demand retrospective payment of the full amount of the tariff with effect from 1 January 2009. Previously, several plant operators had lodged a constitutional complaint against the application of Section 19 para. 1 EEG to existing plants and – having had no success in that respect – had sought temporary legal protection before the Federal Constitutional Court.

7.3.2.4 Date of commissioning

Apart from the plant capacity, the year in which the plant is commissioned is particularly important for determining the level of payment, since the tariff rates fall with each subsequent year of commissioning, because of the principle of tariff degression (see above 7.3.1.3).

Under EEG, a plant is deemed to have been commissioned when it is put into operation for the first time following establishment of its technical operational readiness. Since 1 January 2009 it has been irrelevant whether the generator at the plant is operated with renewable energy sources from the outset or is run initially – for example during start-up – on fossil fuels. Feeding electricity into the grid is not absolutely necessary for the plant to be commissioned, provided that the plant is ready for operation and the plant operator, in turn, has done everything necessary to make feed-in to the grid possible. Trial operation does not constitute the commissioning of a plant.

Subsequent relocation of a commissioned generator to another site does nothing to change the date of commissioning. Even if a generator that has already been used is subsequently installed in a new combined heat and power unit, the commissioning date of this new power generation unit is deemed to be the same as that of the used generator, with the consequence that the period of tariff payment under the EEG is shortened accordingly.

7.3.3 Level of tariff payments in detail

The basic tariff and the various bonuses are described in detail in the following, along with the respective requirements for payment. An overview of the level of payments for biogas plants commissioned in 2011 is shown in Table 7.1.

7.3.3.1 Basic tariff

In relation to the conversion of biogas into electricity, the entitlement to receipt of the basic tariff for biogas plants commissioned in 2011 is as follows: 11.44 cents per kilowatt-hour up to a plant output of 150 kW, 9.00 cents per kilowatt-hour up to a plant output of 500 kW, 8.09 cents per kilowatt-hour up to a plant output of 5 MW and 7.63 cents per kilowatt-hour up to a plant output of 20 MW.

The way in which the basic tariff is determined can be illustrated with the aid of the following example: the CHP unit of a biogas plant commissioned in 2011 has an installed electrical capacity of 210 kW. In 2011 the CHP unit achieves 8,322 full-load hours of operation. The average annual output as defined in EEG is therefore 200 kW. According to the sliding basic tariff, three quarters of the electricity (150 kW of 200 kW) is remunerated at 11.44 cents per kilowatt-hour and one quarter of the electricity (50 kW of 200 kW) at 9.00 cents per kilowatt-hour. The average basic tariff therefore amounts to approximately 10.83 cents per kilowatt-hour.

A prerequisite for entitlement to the basic tariff is that the electricity is generated from biomass within the meaning of the Biomass Ordinance (BiomasseV). The Biomass Ordinance defines biomass as an energy source from phytomass and zoomass and from by-products and waste products whose energy content derives from phytomass and zoomass. The gas produced from biomass is thus also classed as biomass.

All of the feedstocks commonly used in biogas plants are covered by the definition of biomass. It should be noted, however, that, under Section 3 BiomasseV, certain substances are not recognised as biomass within the meaning of the Biomass Ordinance. In addition to certain animal by-products, these also include sewage sludge, sewage treatment gas and landfill gas.

Since 2009 it has also been permissible for EEG plants to use substances that, although not in compliance with the Biomass Ordinance, can be classed as biomass in the broader sense (such as sewage sludge). However, the tariff that is then paid will apply only to that proportion of electricity that is attributable to the use of biomass within the meaning of the Biomass Ordinance.

According to the explanatory memorandum to the Act, however, this relaxation of what is termed the 'exclusivity principle' does not apply to the production of biogas as such: since, to qualify for payment of the tariff, the biogas itself must be biomass within the meaning of Section 27 para. 1 EEG, it must meet the requirements of the Biomass Ordinance. For this reason, the biogas itself must be produced exclusively from biomass within the meaning of the Biomass Ordinance. Subsequently, however, the biogas can be used in combination with other gaseous 'biomass in the broader sense', such as sewage treatment gas (cf. Section 3 No. 11 BiomasseV), for the purposes of electricity generation.

Since 1 January 2009 the EEG feed-in tariff for large plants has been linked to operation in combined heat and power generation. Accordingly, power from biogas plants with a capacity of over 5 MW is only eligible for tariff payment if the heat produced during generation is also utilised. This tightening is intended to encourage operators to ensure that large biogas plants are always built in the vicinity of appropriate heat sinks.

7.3.3.2 Bonuses for use of renewable resources

EEG grants a bonus for the use of renewable resources (cultivated biomass, energy crops: referred to in German as the NawaRo bonus, and in English sometimes as the energy crop bonus) in order to compensate for the higher financial expense associated with the use of purely plant-based input materials in comparison with the use of biomass from wastes, for example. This is meant to promote more efficient use of the biomass arising at agricultural, forestry or horticultural enterprises, especially in relatively small plants, where operation with such renewable resources would often not be economic without an additional financial incentive.

On closer examination, the NawaRo bonus is made up of several different bonuses, sometimes graded according to plant capacity, which, on the one hand, are dependent on the type of substrate used and, on the other, on the type of power generation.

Renewable resources, i.e. energy crops, are defined as follows in Section II. 1 of Annex 2 of EEG:

> *'Energy crops shall mean plants or parts of plants which originate from agricultural, silvicultural or horticultural operations or during landscape management and which have not been treated or modified in any way other than for harvesting, conservation or use in the biomass installation.'*

Manure (slurry) is treated as equal to energy crops.

A list of substrates classed as energy crops is given in the form of a non-exhaustive Positive List. EEG also contains an (exhaustive) Negative List of substrates that are not classed as energy crops and whose use consequently rules out entitlement to the NawaRo bonus.

General NawaRo bonus

The general NawaRo bonus is granted for plants with a capacity of up to 5 MW and – irrespective of the type of renewable biomass used – for installations commissioned in 2011 amounts to 6.86 cents per kilowatt-hour for the share of capacity up to 500 kW and 3.92

Table 7.2: Standard biogas yields of purely plant-based by-products according to the Positive List of EEG (selection) [a]

Purely plant-based by-product	Standard biogas yield according to Section V. of Annex 2 of EEG	
	[kWh_{el}/t FM]	[Nm3 CH_4/t FM]
Spent grains (fresh or pressed)	231	62
Vegetable trailings	100	27
Glycerol from plant oil processing	1,346	364
Potato peel	251	68
Pomace (fresh, untreated)	187	51
Rapeseed oil meal	1,038	281
Rapeseed cake (residual oil content approx. 15%)	1,160	314

a. The full list is given in Chapter 4, Table 4.5.

cents per kilowatt-hour for the share of capacity above 500 kW.

A precondition for granting of the general NawaRo bonus, apart from the exclusive use of energy crops and plant-based by-products, is that the plant operator must keep a log of the input materials showing details of the type, quantity and origin of the biomass used. Also, the plant operator is not allowed to operate another biomass plant that uses substances other than eligible renewable resources on the same plant site.

In addition to energy crops and manure, it is also permissible to use certain purely plant-based by-products in the conversion of biogas into electricity. The permissible by-products are exhaustively specified in a Positive List and include, for example, potato pulp or potato peel, spent grains and cereal vinasse. However, entitlement to the NawaRo bonus is applicable only to the proportion of electricity that is actually generated from the relevant renewable resources or manure. The proportion of electricity eligible for the bonus must be determined on the basis of the statutory standard biogas yields of the purely plant-based by-products and must be verified by an environmental expert.

An overview of all lists of substances used for generating electricity from renewable resources (Positive List of energy crops, Negative List of energy crops, Positive List of purely plant-based by-products) can be taken from Annex 2 of EEG.

For the NawaRo bonus to be granted, if the plant generating electricity from biogas requires a permit under pollution control legislation, the digestate storage facility must also have a gas-tight cover, and additional gas-consuming installations must be provided for the eventuality of a malfuction or over-production. According to the wording of Annex 2 No. I. 4 of EEG, however, only existing digestate storage facilities must be covered; the existence of a digestate storage facility is not a precondition for the NawaRo bonus. It is disputed whether digestate storage facilities also have to have gas-tight covers if – although used by the plant operator – they do not belong to the biogas plant or if methane emissions are no longer to be expected on account of the preceding retention time in other containers. In the absence of a transitional regulation, the additional requirements also apply to plants that were commissioned before 1 January 2009. However, where the addition of such a cover retrospectively would incur costs that could barely be refinanced economically by the operator of the existing plant, in certain circumstances this can be assessed as disproportionate and thus contrary to the law (for further technical considerations regarding the storage of digestates in particular, refer to Section 3.2.3).

Manure bonus

Over and above the general NawaRo bonus, an additional entitlement to a bonus arises from the use of manure for generation of electricity from biogas. The purpose of the manure bonus is to ensure more efficient use of farmyard manure for the production of biogas and to reduce the application of untreated, and therefore methane-emitting, manure on fields. The bonus is paid for a plant capacity of up to 500 kW_{el} only. This limit is set in order to prevent the transport of large quantities of manure over long distances ('manure tourism'), which could otherwise be expected.

According to the authoritative definition in Regulation (EC) No. 1774/2002/EC (EU Hygiene Regulation), manure in this sense is defined as follows:

> *'Excrement and/or urine of farmed animals, with or without litter, or guano, that may be either unprocessed or processed in accordance with Chapter III of Annex VIII or otherwise transformed in biogas or composting plants.'*

The manure bonus is paid on a sliding scale, and for biogas plants commissioned in 2011 amounts to 3.92 cents per kilowatt-hour for the share of capacity up to 150 kW and to 0.98 cents per kilowatt-hour for the share of capacity beyond that up to 500 kW. Plants with a higher capacity can claim the manure bonus on a pro-rata basis accordingly.

A precondition for payment of the manure bonus is that manure must at all times account for at least 30% by mass of the substrates used to produce biogas. The proportion of manure is determined on the basis of the total throughput of biomass in the plant, with the mass being determined by weighing.

The threshold of 30% by mass must be adhered to at all times. The basis for verification of continuous adherence to this minimum proportion is the log of substances used, which the plant operator is obliged to keep. The verification itself must be submitted once a year, by no later than 28 February of the subsequent year, in the form of an expert report by an environmental verifier. The details given in the substances log are used to produce the expert report.

Plants which use **gas from a gas grid** for the purpose of electricity generation are not entitled to the manure bonus. This relates in particular to the use of natural gas classed as biomethane and taken from the natural gas grid (for further details refer to 7.4). Such plants operated on the basis of gas exchange (Gasabtausch) are limited to the higher general NawaRo bonus of up to 7.0 cents per kilowatt-hour. In the author's view, however, power-generating facilities that obtain biogas through a micro gas pipeline directly from the gas production plant are not covered by this exclusion (see also 7.3.2.1). The arrangement set out under the law backs this up: such plants do not use natural gas that is classed as biomethane, but 'genuine' biogas from the pipe, with the consequence that the reference to the legal fiction of Section 27 para. 2 EEG would not have been necessary at all. Furthermore, a single gas pipe is not a gas network within the meaning of No. VI. 2. b) sentence 3 of Annex 2 of EEG. Otherwise the exception would always apply – subject to a legally uncertain differentiation according to the length of the gas pipes – and would no longer be an exception, because every biogas CHP unit is connected to the digester by a gas pipe.

Landscape management bonus

Another additional bonus in connection with the NawaRo bonus is the landscape management bonus, which is paid for the use of clippings, prunings, etc. from landscape management. If a biogas installation mainly uses plants or parts of plants that arise in the course of landscape management, the statutory tariff for biogas plants commissioned in 2011 is increased by 1.96 cents per kilowatt-hour. This bonus, too, is paid for the share of plant capacity up to 500 kW only. Installations with a higher capacity are entitled to claim the bonus on a pro-rata basis.

Landscape management residues comprises residual materials that are not intended to be put to specific use elsewhere and thus are not specifically grown for a purpose but arise as an unavoidable by-product of landscape management. The landscape management bonus creates a utilisation option for these residual substances while at the same time making a contribution to reducing competition for land in the biomass sector, in line with the legislator's intentions.

Details of the individual requirements for entitlement to this new landscape management bonus are still a matter of dispute (see also 4.5). The EEG Clearing Agency completed its recommendation process 2008/48 relating to the landscape management bonus in September 2009. It advocates a broad definition of the term 'landscape management residues'. Accordingly, the weight of the fresh mass is the key reference value for assessing whether a plant uses 'mainly' landscape management material, i.e. over 50%.

Unlike the situation with the manure bonus, EEG does not explicitly stipulate that the requirements for the landscape management bonus must be met at all times. It should therefore be sufficient if the minimum proportion is met when the end-of-year balance is drawn up.

7.3.3.3 Air quality bonus

The amendment of EEG on 1 January 2009 introduced an air quality bonus for biogas plants for the first time. The aim is to reduce the carcinogenic formaldehyde emissions that are formed when biogas is combusted in CHP units. The bonus is therefore sometimes also referred to as the formaldehyde bonus. The bonus is designed to encourage the use of low-emission engines, for example, or the retrofitting of catalytic converters.

The basic tariff is increased by 0.98 cents per kilowatt-hour for biogas plants commissioned in 2011 with a capacity of up to and including 500 kW if formaldehyde emissions do not exceed the statutory limit during plant operation. The bonus is not payable for plants that generate electricity from 'virtual' biomethane, which, according to the provisions of EEG, is fed in at one point in the gas grid and withdrawn at another.

Also, entitlement to the bonus is restricted to biogas plants that are licensable under the Federal German Pollution Control Act (BImSchG). In particular, plants with a rated thermal input of over 1 MW require a licence under BImSchG. If the rated thermal input is below that, the plant is licensable under

BImSchG only in certain instances (for more details see 7.5.1). If a plant therefore requires only a construction permit, but not a licence under BImSchG, its operator is not able to claim the formaldehyde bonus.

Operators of plants that were commissioned before 1 January 2009 can likewise claim the bonus. According to the clear wording of the transitional arrangement under EEG, the same applies to existing plants if the plant does not require a BImSchG licence.

The emission levels at which a plant operator is able to receive the bonus are a matter of dispute. The Act provides that 'the formaldehyde limits established in line with the requirement to minimise emissions set out in the Technical Instructions on Air Quality Control (TA Luft)' must be complied with. The relevant limits are laid down by the responsible authority in the licence notice issued under pollution control legislation. They are based on the emission standards specified in TA Luft, according to which the formaldehyde in the exhaust gas must not exceed a mass concentration of 60 mg/m^3, but must also take account of the requirement to minimise emissions. Based on the requirement to minimise emissions, the authority may also impose lower emission values in individual cases and/or require the plant operator to take additional specific steps to minimise emissions. These considerations suggest that the emission levels laid down in the respective licence notice are also crucial in determining the plant operator's entitlement to the bonus. However, according to a decision by the federal/state working group on pollution control (Bund-/Länder-Arbeitsgemeinschaft Immissionsschutz – LAI) of 18 September 2008, the official notification required for verification of compliance with the limits is issued only if formaldehyde emissions do not exceed 40 mg/m^3.

Verification of compliance with the limits is provided by written certification from the authority responsible for supervision of pollution control under the law of the state in question. The official certification of compliance with the TA Luft formaldehyde limits in line with the requirement to minimise emissions is given to the operator after submission of the emission report to the responsible authority. The certification can then be presented to the grid operator as proof of compliance.

7.3.3.4 CHP bonus

With the CHP bonus, EEG provides a strong financial incentive for using the waste heat that arises in the generation of electricity. Utilisation of the heat increases the overall energy efficiency of a biogas plant and can help to reduce the combustion of fossil fuels. The amendment of EEG further increased the financial incentive, raising the bonus from 2.0 to 3.0 cents per kilowatt-hour (for plants commissioned in 2009). At the same time, however, the requirements with regard to utilisation of the heat were tightened in order to ensure that the heat is put to meaningful use.

For the operator to be able to claim the bonus, the plant must not only produce electricity by cogeneration (combined heat and power), but also have a meaningful strategy for utilising the heat that is produced.

With regard to electricity from cogeneration, EEG makes reference to the Combined Heat and Power Act (Kraft-Wärme-Kopplungsgesetz – KWKG). According to this Act, the plant must simultaneously convert the energy input into electricity and useful heat. For series-produced CHP installations with a capacity of up to 2 MW, compliance with this requirement can be demonstrated by means of appropriate manufacturer's documentation showing the thermal and electrical output and the power-to-heat ratio. For plants with a capacity of over 2 MW, proof must be furnished that the plant satisfies the requirements of Code of Practice FW 308 of the German Heat and Power Association (AGFW).

Under the provisions of EEG, the heat is deemed to be put to good use if it is utilised in line with the Positive List (cf. No. III, Annex 3 of EEG). Examples of entries in the Positive List include supplying certain buildings with a maximum annual thermal input of 200 kWh per m^2 of usable floor area, the feeding of heat into a heat supply network that meets certain requirements, and the use of process heat in certain industrial processes. There are a number of issues that have still not been legally clarified in relation to certain uses of heat mentioned in the Positive List.

Examples of inadmissible uses of heat according to the Negative List (No. IV., Annex 3 of EEG) include the heating of certain buildings without adequate thermal insulation and the use of heat in ORC or Kalina cycle processes. The Negative List is an exhaustive list of inadmissible uses of heat. However, disqualification for the CHP bonus for the use of heat in **ORC or Kalina cycle modules** in accordance with No. IV.2, Annex 3 EEG relates only to that share of the waste heat from a

CHP unit that is used in such an add-on power generation module. As a rule, the use of heat in this way does not justify entitlement to the bonus anyway, because the CHP unit and add-on power generation module will normally constitute a single plant as defined in Section 3 para. 1 EEG, with the consequence that the use of heat in the add-on power generation module does not represent a use of heat outside the plant. However, if the (residual) heat – originally from the CHP unit – is supplied for some other use in accordance with the Positive List after first passing through the subsequent power generation process, then it is the author's opinion that the CHP bonus is payable both for the electricity generated in the add-on power generation module and also for the electricity generated in the CHP unit. Treating the electricity generated in the CHP unit as CHP electricity is not contradictory to No. IV.2, Annex 3 EEG, because the proportion of heat consumed in the add-on power generation process is not taken into account when the amount of externally utilised heat is determined. Limiting the entitlement to the CHP bonus to the electricity generated in the add-on power generation module, on the other hand, would lead to considerable unjustified discrimination against those plants which have an additional power-generation module as well as the combined heat and power unit.

If the heat is not utilised in line with the Positive List, the plant operator can still receive the bonus under certain circumstances. This requires each of the following conditions to be met:

- the intended use of the heat must not be included in the Negative List,
- the generated heat must replace an amount of heat from fossil fuels to a comparable extent, i.e. to at least 75%, and
- additional costs amounting to at least €100 per kW of heat output must arise as a result of the supply of heat.

It is not clear how 'replace' should be understood as a condition for entitlement. In new buildings that are supplied with waste heat from the CHP unit from the outset, actual replacement of fossil energy sources is not possible as such, so this is at best a potential replacement. To that extent it can be assumed that a potential replacement will also suffice. Accordingly, the plant operator must explain that fossil energy sources would have been used if the heat had not been made available from the CHP unit.

The additional costs that can be taken into account are costs for heat exchangers, steam generators, pipes and similar technical facilities, but not higher fuel costs.

Verification that the heat has been utilised in line with the Positive List and that fossil fuels have been replaced, along with indication of the additional capital expenditure required, must be furnished by the expert report of an approved environmental verifier.

7.3.3.5 Technology bonus

The technology bonus creates a financial incentive to use innovative technologies and systems that are particularly energy-efficient and therefore have a reduced impact on the environment and climate.

The bonus is paid for the use of biogas that has been processed to natural gas quality as well as for the use of innovative plant technology for the generation of electricity. Gas processing is supported when the following criteria are met:

- maximum methane emissions of 0.5% arise during processing,
- power consumption for processing does not exceed 0.5 kWh per normal cubic metre of raw gas,
- all of the process heat for processing and production of biogas is made available from renewable energy sources or from waste heat from the plant itself, and
- the maximum capacity of the gas processing installation is 700 normal cubic metres of processed gas per hour.

The technology bonus amounts to 2.0 ct/kWh for all the electricity generated from gas produced in such gas processing plants up to a maximum capacity of the gas processing plant of 350 normal cubic metres of processed gas per hour, and to 1.0 ct/kWh for plants with a maximum capacity of up to 700 normal cubic metres per hour.

According to Annex 1 EEG, particularly innovative plant technologies relating to the generation of electricity from biogas include fuel cells, gas turbines, steam engines, organic Rankine cycle systems, multi-fuel installations such as Kalina cycle systems, and Stirling engines. In addition, support is given to the thermochemical conversion of straw and to plants designed exclusively for the digestion of biowastes with post-rotting treatment.

The bonus is no longer granted for dry digestion in plants commissioned after 31 December 2008, because dry digestion plants do not conform to the statutory requirement for an innovative procedure that reduces the impact on the climate.

A precondition of support for the above-mentioned technologies and processes is that either they must achieve an electrical efficiency of at least 45% or that use must be made of the heat at least for part of the time and to a certain extent.

When innovative plant technologies are used, a bonus of 2.0 ct/kWh is paid. However, the bonus is granted for only that proportion of the electricity that is produced using such technologies or processes. If a CHP unit also generates electricity using other methods that do not meet the requirements, the plant operator does not receive a technology bonus for that proportion.

7.4 Gas processing and feed-in

It does not always make economic and environmental sense to use the biogas at the location where it is produced, i.e. in the vicinity of the biogas plant. The generation of electricity is inevitably accompanied by the production of heat, which often cannot be put to meaningful use at the biogas plant site. In certain circumstances, therefore, it may make sense to break the link between biogas generation and biogas utilisation. As well as installing a raw biogas pipeline, by means of which the biogas can be transported over distances of between a few hundred metres and several kilometres for use in a satellite plant (for further details see 7.3.2.1), it is also possible to consider processing the gas and feeding it into the public natural gas grid. After it has been fed into the grid, the biogas can then be 'virtually' withdrawn from any point in the grid and converted into electricity and heat in a combined heat and power plant.

7.4.1 Requirements for payment of EEG tariff

Operators of CHP units who use biomethane in their plants in this way essentially receive the same payment as they do if the gas is converted directly into electricity on the site of the biogas plant; the same applies if the biogas is fed through a micro gas pipeline. In addition, if the biogas is fed into the natural gas grid, the technology bonus is payable for gas processing: according to Annex 1 EEG, the payment is increased by 2.0 ct/kWh if the biogas has been processed to natural gas quality and certain requirements have been met (for further details see 7.3.3.5). Plant operators cannot, however, claim the air quality bonus (see 7.3.3.3) or the manure bonus (see 7.3.3.2) if the biogas is fed through to the grid.

According to Section 27 para. 3 EEG, however, entitlement to payment of the EEG tariff applies only to the CHP proportion of the electricity, i.e. the electricity that is generated with simultaneous use of the heat within the meaning of Annex 3 EEG. Ultimately, therefore, only heat-led CHP units will benefit from the support for gas processing under EEG.

Another prerequisite for entitlement to payment is that the CHP plant must use only biomethane. In this case, the exclusivity principle means that it is not possible to switch operation between conventional natural gas and biogas. Rather, the operator of the CHP unit must ensure that, by the end of the calendar year, a quantity of biogas equivalent to the quantity of gas actually used has been fed elsewhere into the gas grid and has been assigned to his CHP unit. Otherwise the operator risks losing the whole of his entitlement to payment of the EEG tariff.

7.4.2 Transport from the feed-in point to the CHP unit

As the biomethane that is fed into the grid immediately mixes with the natural gas in the grid, physical transport of the biomethane to a specific CHP unit is not possible. In fact, conventional natural gas is used in the CHP unit. In legal terms, however, the natural gas used in the CHP unit is classed as biogas, provided the conditions set out in Section 27 para. 2 EEG are met.

The first condition is that the quantity of gas withdrawn from the grid must be thermally equivalent to the quantity of gas from biomass that is fed elsewhere into the gas grid. It is sufficient if the quantities are equivalent at the end of the calendar year.

Another condition for entitlement to the tariff is that it must actually be possible for the fed-in quantity of gas to be assigned to a certain CHP unit. In the absence of physical transport, it is essential for there to be a contractual relationship between the infeeder and the operator of the CHP unit. Apart from a simple biomethane supply contract, stating that the quantities of biomethane fed in are supplied to the CHP unit operator, it is also possible to enter into other contractual relationships – such as involving wholesalers or making use of tradable certificates or a central biomethane register. The biogas infeeder must ensure that the biogenic character of the biomethane fed in is not marketed twice, but is always assigned exclusively to one CHP unit.

7.4.2.1 Transport model

Biogas infeeders can fulfil their contractually agreed supply obligation in particular by acting as gas traders and undertaking to supply the withdrawal point used by the CHP unit operator. In this case, although there is no physical transport of the biomethane from the feed-in point to the withdrawal point, there is virtual transport in accordance with the rules of the gas industry. Biogas infeeders usually use biogas balancing group contracts for this purpose. The mere fact that the withdrawal point for the CHP unit is assigned to a biogas balancing group is not, however, sufficient evidence that the CHP unit is the exclusive user of the biomethane. The background to this is that, if the biogas balancing group has a negative balance at the end of the year, the gas grid operator is not obliged to make good that balance with biomethane. Consequently, even if they are supplied by the biogas infeeder, plant operators have to produce evidence themselves to the power grid operator that the thermal equivalent of the corresponding quantity of biogas has indeed been fed in during the calendar year and should be assigned to their CHP unit.

7.4.2.2 Certificate model

Alternatively, the biogas infeeder can forego supplying biomethane to the withdrawal point and instead merely allow the CHP unit operator to utilise the biogenic character of the fed-in biomethane in return for payment. To this end, the biogas infeeder will market the fed-in gas like conventional natural gas and will, in this way, separate the biogenic character from the physically injected gas. The biogenic character can then – as also in the power sector – be presented in isolation, for example in the form of certificates scrutinised by an independent body. The CHP operator continues to obtain conventional natural gas from a natural gas trader and merely purchases the necessary quantity of biomethane certificates from the biogas infeeder. What still remains problematical with the certificate model, however, is that the plant operator has to ensure that the gas properties and plant characteristics required for payment of the various tariffs and bonuses under EEG are adequately documented and that double selling is ruled out. It is therefore essential that the use of certificates should be agreed in advance with the responsible power grid operator.

The planned establishment of a biomethane register, which had not yet been completed at the time of going to press, is intended to simplify the trade in biomethane.

7.4.3 Legal framework for grid connection and grid use

Gas processing and feed-in not only causes particular technical difficulties, but it is also associated with a number of legal challenges. However, the general framework for gas feed-in to the grid has been significantly improved by the amendment of the gas network access ordinance (GasNZV) and the ordinance on gas network tariffs (GasNEV). GasNZV and GasNEV were first amended in April 2008 and then again in July 2010.[1]

7.4.3.1 Priority grid connection

According to the amended gas network access ordinance, the gas grid operator is obliged to give priority to connecting biogas processing and feed-in installations to the gas grid. The grid operator is permitted to refuse grid connection and feed-in only if this is technically impossible or economically unreasonable. Provided that the grid is technically and physically capable of receiving the injected quantities of gas, the grid operator cannot refuse to accept the gas, even if there is a risk of capacity bottlenecks on account of existing transport contracts. The grid operator is obliged to take all economically reasonable steps to enable feed-in to take place all year round. Such steps may include, for example, the installation of a compressor in order to enable the gas to be returned to a higher pressure level, especially in the summer months, when the feed-in quantity significantly exceeds the quantity of gas withdrawn from the particular section of the grid.

7.4.3.2 Ownership and cost of grid connection

The amended gas network access ordinance also provides numerous privileges for the infeeder with regard to the costs of grid connection. For instance, according to the amended GasNZV, which had not yet been promulgated at the time of going to press, the infeeder will have to pay only €250,000 of the capital costs of grid connection, including the first kilometre of the connecting pipeline to the public natural gas grid. If the length of the connecting pipeline is over

1. The amendment of July 2010 had not yet been passed and promulgated at the time of going to press.

one kilometre, the grid operator will pay 75% of the additional costs up to a length of 10 kilometres. The grid connection becomes the property of the grid operator. The grid operator also has to pay for all maintenance and ongoing operating costs. Furthermore, according to the amended GasNZV, which had not yet been promulgated at the time of going to press, the grid operator must also guarantee a minimum availability of 96%.

7.4.3.3 Balancing of biomethane feed-in

In addition to the requirement that a certain quantity of gas be assigned to a certain CHP unit for payment of the EEG tariff, it is also necessary that the fed-in gas be balanced and transported in accordance with gas industry rules. Also in this regard, the amended GasNZV makes life easier for biogas infeeders. For instance, provision is now made for special biogas balancing groups with a greater flexibility range of 25% and a balancing period of 12 months. Using this kind of biogas balancing group makes it possible, for example, to use the fed-in biogas in a heat-led CHP unit, without feed-in having to be throttled back in the summer months in accordance with the CHP operating regime.

7.5 Heat recovery and supply

If a biogas CHP unit is operated in cogeneration mode, the waste heat must be utilised as part of a permissible heat recovery concept in order to qualify for the CHP bonus (for details of the conditions for entitlement to the CHP bonus, see 7.3.3.4). For the CHP bonus to be claimed, verification must be provided that the heat is utilised in line with the Positive List, No. III in Annex 3 EEG. This applies to all plants commissioned after 1 January 2009. There is entitlement to the CHP bonus if the other criteria for payment of the bonus are met, regardless of whether the heat is used by a third party or by the plant operator.

7.5.1 Legal framework

If the heat is utilised in line with No. III. 2, Annex 3 EEG (feed-in to a heat network), incentives are currently available for the construction of certain types of heat networks both through the **market incentive programme** (see under 7.1) and also through the Combined Heat and Power Act (KWKG). Eligible heat networks are characterised by the fact that they obtain a certain proportion of their heat either from combined heat and power generation or from renewable energy sources. For the immediate future, this has put in place the basis for the creation of an increasing number of EEG heat networks and CHP heat networks.

The growing importance of group heating schemes and district heating networks is further underlined by the fact that, pursuant to Section 16 **EEWärmeG** (Renewable Energies Heat Act), municipalities and local government associations are now expressly able to avail themselves of authorisations under state law to establish compulsory connection and use with connection to a public local or district heating supply grid, including for the purposes of climate change mitigation and the conservation of resources. This eliminates any previous uncertainty about the admissibility of compulsory connection and use under the respective municipal codes. This is designed to encourage local authorities to issue corresponding connection and use regulations for public heat supply networks in which a proportion of the final energy originates from renewable energy sources or predominantly from CHP plants.

Furthermore, the Renewable Energies Heat Act increases the potential offtaker market for biogas as well as for the heat arising from the conversion of biogas into electricity. This is because the owners of new buildings for which a construction application is submitted after 31 December 2008 can meet their obligations to use renewable energies (applicable under the Act since 2009) by meeting a proportion of their heating needs from biogas CHP plants. Where the obligation to use renewable energies must be met exclusively by the use of biogas, owners must meet at least 30% of their heating energy needs through the use of gaseous biomass. Where upgraded and injected biomethane is used to supply heat, particular requirements have to be met in accordance with No. II. 1 of the Annex to the Renewable Energies Heat Act. Alternatively, the obligation to use renewable energies is deemed to have been satisfied if a building's heat demand is met from a heat network that obtains a significant proportion of its heat from renewable energy sources – for example from the waste heat from a biogas CHP unit.

Apart from establishing an entitlement to the CHP bonus, the supply of heat to third parties is also otherwise an increasingly important profitability factor for many projects.

7.5.2 Supply of heat

The plant operator supplies the heat either to a heat network operator or directly to the heat offtaker. In the latter case, there are essentially two different supply strategies. The first is to operate the CHP unit at the site of the biogas plant and to supply the arising heat from there to the heat offtaker through a heat pipeline or a heat network. The other option, which is even more efficient, is to transport the biogas through a raw gas pipeline or – after appropriate upgrading – through the public natural gas grid to the location where the heat is required and convert the gas into electricity there. This approach avoids heat losses during transport.

Where the plant operator sells the heat to an intermediate heat network operator, there is no direct contractual relationship between plant operator and end user. The heat network operator and the end user enter into a separate heat supply contract. Where, however, the plant operator himself acts as the heat supplier, he enters directly into a heat supply contract with the heat offtaker. If the plant operator prefers not to take on the obligations associated with being a heat supplier, he can contract the services of a third party.

7.5.3 Heat networks

As a rule, no special permit is required to set up a heat network. The heat network operator must, however, pay attention to rights of use with regard to laying of heat pipelines across third-party land, which will be necessary in most cases. In addition to entering into a land use contract with the respective land owner, which will, in particular, regulate the payment for the right to use the land, it is also advisable in this connection to protect the right to use the land, for example by registering an easement in the land registry. This is the only way of ensuring that the heat supplier will remain entitled to use the land for the heat pipeline if the land is sold to another owner. Where a heat pipeline is laid along a public highway, the heat network operator must enter into an easement agreement with the authority responsible for road construction and maintenance. This may require payment of a fixed fee or a fee determined on the basis of the kilowatt-hours supplied.

7.6 Recommended further reading

Altrock, M.; Oschmann, V.; Theobald, C. (eds.): EEG, Kommentar, 2nd edition, Munich, 2008

Battis, U.; Krautzberger, M.; Löhr, R.-P.: Baugesetzbuch, 11th edition, Munich, 2009

Frenz, W.; Müggenborg, H.-J. (eds.): EEG, Kommentar, Berlin, 2009

Loibl, H.; Maslaton, M.; v. Bredow, H. (eds.): Biogasanlagen im EEG, Berlin, 2009 (2nd edition forthcoming)

Reshöft, J. (ed.): EEG, Kommentar, 3rd edition, Baden-Baden, 2009

Salje, P.: EEG - Gesetz für den Vorrang Erneuerbarer Energien, 5th edition, Cologne/Munich, 2009

Jarass, H. D.: Bundesimmissionsschutzgesetz, 8th edition, Munich, 2009

Landmann/ Rohmer: Umweltrecht, vol. I / II, Munich, 2009

7.7 List of sources

AGFW - Arbeitsblatt FW 308 (Zertifizierung von KWK-Anlagen - Ermittlung des KWK-Stromes -)

AVBFernwärmeV – Verordnung über Allgemeine Bedingungen für die Versorgung mit Fernwärme (ordinance on general conditions for supply of district heating) – of 20 June 1980 (BGBl. I p. 742), last amended by Article 20 of the Act of 9 December 2004 (BGBl. I p. 3214)

BauGB – Baugesetzbuch (Federal Building Code) as amended and promulgated on 23 September 2004 (BGBl. I p. 2414), last amended by Article 4 of the Act of 31 July 2009 (BGBl. I p. 2585)

BauNVO – Baunutzungsverordnung (land use regulations) – as amended and promulgated on 23 January 1990 (BGBl. I p. 132), last amended by Article 3 of the Act of 22 April 1993 (BGBl. I p. 466)

BImSchG – Bundes-Immissionsschutzgesetz (Pollution Control Act) as amended and promulgated on 26 September 2002 (BGBl. I p. 3830), last amended by Article 2 of the Act of 11 August 2009 (BGBl. I p. 2723)

4th Implementing Regulation, BImSchV – Verordnung über genehmigungsbedürftige Anlagen (Pollution Control Act, Ordinance on Installations Requiring a Permit) as amended and promulgated on 14 March 1997 (BGBl. I p. 504), last amended by Article 13 of the Act of 11 August 2009 (BGBl. I p. 2723)

BioAbfV – Bioabfallverordnung (Ordinance on Biowastes) – as amended and promulgated on 21 September 1998 (BGBl. I p. 2955), last amended by Article 5 of the Ordinance of 20 October 2006 (BGBl. I p. 2298)

BiomasseV – Biomasseverordnung (Biomass Ordinance) – of 21 June 2001 (BGBl. I p. 1234), amended by the Ordinance of 9 August 2005 (BGBl. I p. 2419)

EEG – Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act) – of 25 October 2008 (BGBl. I p. 2074), last amended by Article 12 of the Act of 22 December 2009 (BGBl. I p. 3950)

EEWärmeG – Erneuerbare-Energien-Wärmegesetz (Renewable Energies Heat Act) – of 7 August 2008 (BGBl. I p. 1658), amended by Article 3 of the Act of 15 July 2009 (BGBl. I p. 1804)

DüV – Düngeverordnung (Fertiliser Application Ordinance) as amended and promulgated on 27 February 2007 (BGBl. I p. 221), last amended by Article 18 of the Act of 31 July 2009 (BGBl. I p. 2585)

DüMV – Düngemittelverordnung (Fertiliser Ordinance) – of 16 December 2008 (BGBl. I p. 2524), last amended by Article 1 of the Ordinance of 14 December 2009 (BGBl. I p. 3905)

GasNEV – Gasnetzentgeltverordnung (Ordinance on Gas Network Tariffs) – of 25 July 2005 (BGBl. I p. 2197), last amended by Article 2 para. 4 of the Ordinance of 17 October 2008 (BGBl. I p. 2006)

GasNZV – Gasnetzzugangsverordnung (Gas Network Access Ordinance) – of 25 July 2005 (BGBl. I p. 2210), last amended by Article 2 para. 3 of the Ordinance of 17 October 2008 (BGBl. I p. 2006)

KrW-/AbfG – Kreislaufwirtschafts- und Abfallgesetz (Product Recycling and Waste Management Act) of 27 September 1994 (BGBl. I p. 2705), last amended by Article 3 of the Act of 11 August 2009 (BGBl. I p. 2723)

KWKG 2002 – Kraft-Wärme-Kopplungsgesetz (Law on Cogeneration) of 19 March 2002 (BGBl. I p. 1092), last amended by Article 5 of the Law of 21 August 2009 (BGBl. I p. 2870)

TA Lärm – Technische Anleitung zum Schutz gegen Lärm (Technical Instructions on Noise Abatement) – of 26 August 1998 (GMBl. 1998, p. 503)

TA Luft – Technische Anleitung zur Reinhaltung der Luft (Technical Instructions on Air Quality Control) – of 24 July 2002 (GMBl. 2002, p. 511)

TierNebG – Tierische Nebenprodukte-Beseitigungsgesetz (Disposal of Animal By-Products Act) – of 25 January 2004 (BGBl. I p. 82), last amended by Article 2 of the Ordinance of 7 May 2009 (BGBl. I p. 1044)

TierNebV – Tierische Nebenprodukte-Beseitigungsverordnung (Ordinance implementing the Disposal of Animal By-Products Act) – of 27 July 2006 (BGBl. I p. 1735), last amended by Article 19 of the Act of 31 July 2009 (BGBl. I p. 2585)

UVPG – Gesetz über die Umweltverträglichkeitsprüfung (Environmental Impact Assessment Act) as amended and promulgated on 25 June 2005 (BGBl. I p. 1757, 2797), last amended by Article 1 of the Act of 31 July 2009 (BGBl. I p. 2723)

VO 1774/2002/EG – Regulation (EC) No. 1774/2002 of the European Parliament and of the Council of 3 October 2002 laying down health rules concerning animal by-products not intended for human consumption (OJ L 273 p. 1), last amended by Regulation (EC) No. 1432/2007 of 5 December 2007 (OJ L 320 p. 13)

VO 181/2006/EG – Commission Regulation (EC) No. 181/2006 of 1 February 2006 implementing Regulation (EC) No. 1774/2002 as regards organic fertilisers and soil improvers other than manure and amending that regulation (OJ L 29 p. 31)

Economics

8

When a potential operator is deciding whether to build a biogas plant, the crucial consideration is: can the future plant be operated at a profit?

The economic profitability of biogas plants therefore needs to be assessed. To this end, a suitable method is presented in the following with reference to model plants.

8.1 Description of model plants – assumptions and key parameters

The conditions applying to tariff payments and the restrictions on the use of substrates as set out under EEG 2009 were taken into account both in the sizing of the plants and in the choice of substrates. The year of commissioning was assumed to be 2011.

8.1.1 Plant capacity

Plant capacity has steadily grown in recent years. However, following the establishment of the manure bonus in EEG 2009 [8-1], smaller plants in the capacity range around 150 kW_{el} are once again being built in greater numbers. In order to reflect the spectrum of plants actually in existence, nine model plants with electrical capacities from 75 kW to 1 MW and one biogas processing plant were generated (cf. Table 8.1). Plant sizing took account of both the legal situation concerning payments, with the EEG capacity thresholds of 150 and 500 kW_{el}, and also the licensing thresholds under the Pollution Control Act . In addition, one plant is used as an example to demonstrate the costs that are incurred in producing gas for feed-in to a natural gas grid.

8.1.2 Substrates

The chosen substrates are substances that are commonly found in German agriculture and are suitable for use in the here presented biogas plants. These include farm fertilisers and silages from agricultural sources as well as by-products from the processing of plant-based raw materials. Organic wastes are another group of substances that were taken into account. Whereas the bonus for renewable resources (NawaRo bonus) is reduced proportionately when by-products are used, it is not payable at all if wastes are used for the entire plant.

The table below shows the key data of the substrates used. The gas yield data is based on the standard values from the publication issued by KTBL (Association for Technology and Structures in Agriculture) 'Gasausbeute in landwirtschaftlichen Biogasanlagen' (gas yield in agricultural biogas plants), which were drawn up by the KTBL working group on biogas yields (cf. Table 8.2) [8-4].

It is assumed that the biogas plant is on the same site as the livestock, with the result that no costs are incurred for the use of farm fertilisers. If manure has to be delivered from elsewhere, additional allowance must be made for transport costs. The costs of supplying the renewable resources (energy crops) are assumed to be the average costs according to the KTBL database.

Plant-based by-products and wastes are valued at the market prices given in the table. The prices include delivery to the site of the biogas plant. Seasonal substrates are stored at the biogas plant. The prices of silages relate to freshly delivered harvested products. The silage losses amounting to 12% are at the expense of the biogas plant. The plants have an interim storage capacity of about one week for substrates that arise continuously. For substrates that require hygienisation by german law, it is assumed

Table 8.1: Overview and description of the model plants

Model	Capacity	Description
I	75 kW_{el}	Use of energy crops and ≥ 30% manure (sufficient to obtain the manure bonus); in the examples: at least 34% of the fresh mass used each day is manure
II	150 kW_{el}	
III	350 kW_{el}	
IV	350 kW_{el}	Digestion of 100% energy crops; separation and recirculation
V	500 kW_{el}	Digestion of manure and plant-based by-products in accordance with Annex 2 EEG
VI	500 kW_{el}	Digestion of 100% energy crops; separation and recirculation
VII	500 kW_{el}	Digestion of manure and biowastes. Plants that digest biowastes receive no NawaRo bonus and therefore also no manure bonus. Manure as a proportion of fresh mass can therefore be below 30%.
VIII	1,000 kW_{el}	Digestion of 100% energy crops; separation and recirculation
IX	500 kW_{el}	Dry digestion with garage-type digester; use of solid dung and energy crops
X	500 m^3/h[a]	Design and substrate input as for plant VIII; gas processing and feed-in instead of CHP unit

a. Throughput of raw gas per hour (500 m^3/h roughly corresponds to a capacity of 1 MW_{el})

Table 8.2: Substrate characteristics and prices

Substrates	DM %	VS % of DM	Biogas yield Nm^3/t VS	Methane content %	Methane yield Nm^3/t	Purchase price €/t FM
Cattle slurry, with fodder residues	8	80	370	55	13	0
Pig slurry	6	80	400	60	12	0
Cattle dung	25	80	450	55	50	0
Maize silage, wax ripe, grain rich	35	96	650	52	114	31
Cereal grains, comminuted	87	98	700	53	316	120
Grass silage	25	88	560	54	67	34
WCC silage, average grain content	40	94	520	52	102	30
Glycerol	100	99	850	50	421	80
Rapeseed cake, 15% residual oil content	91	93	680	63	363	175
Cereals, trailings	89	94	656	54	295	30
Catering waste, average fat content[a]	16	87	680	60	57	5
Grease trap waste [a]	5	90	1000	68	31	0
Biowaste [a]	40	50	615	60	74	0

a. Substrates are hygienised before delivery

that they are hygienised prior to delivery; this is taken into account in the price.

Table 8.3 provides an overview of the type and quantity of the substrates used in the various model plants. The substrates were chosen such that plants I–III and V receive the manure bonus, with a proportion of farm fertilisers of over 30%.

Because it uses plant-based by-products (according to Annex 2, EEG 2009, cf. Section 7.3.3.2), plant V receives a reduced bonus for energy crops. Plant VII does not receive any bonus for energy crops, because it uses wastes.

Table 8.3: Substrates used in the model plants [t FM/year]

Model plants / Substrates used	I	II	III	IV	V	VI	VII	VIII	IX	X
	30% manure, 70% energy crops			100% energy crops	By-products	100% energy crops	Biowastes	100% energy crops	DD [a]	Gas processing
	75 kW_{el}	150 kW_{el}	350 kW_{el}	350 kW_{el}	500 kW_{el}	500 kW_{el}	500 kW_{el}	1,000 kW_{el}	500 kW_{el}	500 m^3/h [b]
Cattle slurry	750	1,500	3,000		3,500		4,000			
Pig slurry					3,500					
Cattle dung									2,000	
Maize, silage, wax ripe, grain rich	1,250	2,500	5,750	5,500		7,400		14,000	5,000	14,000
Cereal grains, comminuted			200			200		500		500
Grass silage	200	200							2,600	
WCC silage, average grain content				1,300		1,500		2,500	2,100	2,500
Glycerol					1,000					
Rapeseed cake, 15% residual oil content					1,000					
Cereals (trailings)					620					
Catering waste, average fat content							8,000			
Grease from grease traps							4,600			
Biowaste							5,500			

a. DD: dry digestion
b. Throughput of raw gas per hour

Plants IV, VI, VIII and X use 100% energy crops within the meaning of EEG. In order to ensure the pumpability of the substrate, part of the digestate is separated and the liquid phase is recirculated.

Plants VIII and X differ only in how the gas is utilised. Whereas plant VIII generates heat and power, the gas produced in plant X is processed ready to be fed into the natural gas grid. Plant IX is a dry digestion plant using garage-type digesters. The solids used in this case are cattle dung and silages.

8.1.3 Biological and technical design

The substrates for the model plants were chosen such that each plant achieves a level of capacity utilisation of 8,000 full-load hours per year with the quantity of biogas/energy to be expected from the substrates. Once the types and quantities of substrates had been chosen, the design variables were determined for substrate storage, substrate loading, digesters and digestate storage facilities.

In order to ensure biologically and technically stable operation of the plants while paying due attention to aspects of profitability, the parameters listed in Table 8.4 were applied.

Model plants I and II are run as single-stage plants, while all other wet digestion plants are operated under two-stage process control. Model plants VIII and X each have two digesters in the first stage and two digesters in the second stage, operated in parallel.

Table 8.5 shows which technologies and components, grouped into assemblies, were included in the model plants.

Various other assumptions were made for the calculations for the model plants. These are outlined below.

Solids loading system: With the exception of model

Table 8.4: Assumptions for key technical and process-related parameters and design variables of the model plants

Selected assumptions for technical design	
Digester organic loading rate	Max. 2.5 kg VS/m³ of useful digester volume (total) per day
Process control	Single-stage process control: < 350 kW_{el} Two-stage process control: ≥ 350 kW_{el}
Digester organic loading rate of first digester in two-stage or multi-stage system	Max. 5.0 kg VS/m³ of useful digester volume per day
Dry matter content in mixture	Max. 30% DM, otherwise separation and recirculation (except for dry digestion)
Mobile technology	Tractor with front loader or wheel loader, depending on quantity of substrate to be moved (based on data from KTBL database)
Digester volume	Digester volume required for an organic loading rate of 2.5 kg VS/m³ per day, plus 10% safety margin, minimum retention time 30 days
Installed agitator power and equipment	Digester, first stage: 20-30 W/m³ of digester volume; Digester, second stage: 10-20 W/m³ of digester volume; depending on substrate properties, number and type of agitators, according to size of digester
Digestate storage	Storage capacity for a duration of 6 months, for the entire quantity of digestate arising (incl. manure part), plus 10% safety margin, with gas-tight cover
Sale of heat	Heat sold: 30% of generated heat energy, heat price 2 ct/kWh, interface at heat exchanger of CHP unit
Type of CHP unit	75 kW and 150 kW: pilot ignition gas engine; ≥ 350 kW: gas spark ignition engine
CHP efficiency	Between 34% (75 kW) and 40% (1,000 kW) (based on data from ASUE, CHP parameters 2005)
CHP full-load hours	8,000 full-load hours per year This is the target and assumes optimum plant operation

Table 8.5: Incorporated technology of the model plants

Assembly	Description and main components
Substrate store	Silo slabs of concrete, where appropriate with concrete walls, steel tank for intermediate storage of substrates delivered in liquid form
Receiving tank	Concrete tank Stirring, comminution and pumping equipment, where appropriate with filling shaft, substrate pipes, level measuring system, leak detection
Solids loading system (energy crops only)	Screw conveyor, plunger or feed mixer loading, loading hopper, weighing equipment, digester charging system
Digester	Upright concrete container, above ground Heating, insulation, cladding, agitator equipment, gas-tight cover (gas storage), substrate/gas pipes, biological desulphurisation, instrumentation & control and safety equipment, leak detection
≥ 500 kW_{el} external biological desulphurisation	Desulphurisation including technical equipment and piping
CHP unit	Pilot ignition gas engine or gas spark ignition engine Engine block, generator, heat exchanger, heat distributor, emergency cooler, engine control system, gas pipes, instrumentation & control and safety equipment, heat and electricity meters, sensors, condensate separator, compressed air station, where applicable also with gas system, oil tank, container
Gas feed-in	High-pressure water scrubbing, liquefied gas metering, gas analysis, odorisation, connecting pipes, biogas boiler
Gas flare	Gas flare including gas systems
Digestate storage	Concrete tank Agitator equipment, substrate pipes, unloading equipment, leak detection, gas-tight cover, instrumentation & control and safety equipment, biological desulphurisation, gas pipes, where applicable with separator

plant VII, a solids loading system is required for all plants because of the type and quantity of the substrates used. In model VII the hygienised substrates are delivered in pumpable form and are mixed in an intake pit.

Digestate storage: All model plants have storage tanks with gas-tight covers to hold the quantity of digestate arising in six months. This takes account of the fact that digestate storage facilities with gas-tight covers are obligatory under EEG for receipt of the NawaRo bonus for biogas plants licensable under the Pollution Control Act (BImSchG). Retrofitting of existing slurry storage tanks is often technically impossible.

Hygienisation: Substrates requiring hygienisation are processed in model plant VII. It is assumed that the substrates are delivered in a hygienised state, so there is no need for technical components for hygienisation. The cost of hygienisation is already included in the price of the substrate.

Gas feed-in: The gas feed-in system covers the entire process chain, including feed-in to the natural gas grid. However, the costs arising in relation to supply of the raw/purified gas are also included, as various cooperation models with grid operators and gas suppliers are used in practice. According to Section 33 para. 1 of the amended Gas Network Access Ordinance, the grid operator must pay 75% of the grid connection costs while the infeeder pays 25% (see also Section 7.4.3.2). For grid connections up to one kilometre in length, the share of costs borne by the infeeder is capped at €250,000. Ongoing running costs are paid by the grid operator. For model plant X it was assumed that the infeeder must pay the grid connection costs of €250,000.

8.1.4 Technical and process-related parameters

Tables 8.6, 8.7 and 8.8 provide an overview of the technical and process-related parameters of the model plants.

Table 8.6: Technical and process-related parameters of model plants I to V

Technical and process-related data	Unit	I	II	III	IV	V
		30% manure, 70% energy crops			100% energy crops	By-products
		75 kW_{el}	150 kW_{el}	350 kW_{el}	350 kW_{el}	500 kW_{el}
Electrical capacity	kW	75	150	350	350	500
Type of engine		Pilot ignition	Pilot ignition	Gas spark ign.	Gas spark ign.	Gas spark ign.
Electrical efficiency	%	34	36	37	37	38
Thermal efficiency	%	44	42	44	44	43
Gross digester volume	m³	620	1,200	2,800	3,000	3,400
Digestate storage volume	m³	1,100	2,000	4,100	2,800	4,100
Dry matter content of substrate mixture (incl. recirculate)	%	24.9	24.9	27.1	30.9	30.7
Average hydraulic retention time	d	93	94	103	119	116
Digester organic loading rate	kg VS/m³ · d	2.5	2.5	2.5	2.4	2.5
Gas yield	m³/a	315,400	606,160	1,446,204	1,455,376	1,906,639
Methane content	%	52.3	52.3	52.2	52.0	55.2
Electricity fed in	kWh/a	601,114	1,203,542	2,794,798	2,800,143	3,999,803
Heat generated	kWh/a	777,045	1,405,332	3,364,804	3,364,388	4,573,059

Table 8.7: Technical and process-related parameters of model plants VI to X

Technical and process-related data	Unit	VI 100% energy crops 500 kW_{el}	VII Biowastes 500 kW_{el}	VIII 100% energy crops 1,000 kW_{el}	IX Dry digestion 500 kW_{el}
Electrical capacity	kW	500	500	1,000	500
Type of engine		Gas spark ign.	Gas spark ign.	Gas spark ign.	Gas spark ign.
Electrical efficiency	%	38	38	40	38
Thermal efficiency	%	43	43	42	43
Gross digester volume	m^3	4,000	3,400	7,400	3,900
Digestate storage volume	m^3	3,800	11,400	6,800	0
Dry matter content of substrate mixture (incl. recirculate)	%	30.7	18.2	30.6	32.0
Average hydraulic retention time	d	113	51	110	24 (~69)[a]
Digester organic loading rate	kg VS/m^3 · d	2.5	2.4	2.5	2.5
Gas yield	m^3/a	2,028,804	1,735,468	3,844,810	2,002,912
Methane content	%	52.1	60.7	52.1	52.6
Electricity fed in	kWh/a	4,013,453	4,001,798	8,009,141	4,002,618
Heat generated	kWh/a	4,572,051	4,572,912	8,307,117	4,572,851

a. in brackets: total retention time as a result of recirculation of the digestate as an inoculation material

Table 8.8: Technical and process-related parameters of model plant X

Technical and process-related data	Unit	X Gas processing
Nominal capacity	m^3/h	500
Average flow rate	m^3/h	439
Capacity utilisation	h/a	7,690
Consumption of biogas for digester heating	%	5
Methane loss	%	2
Calorific value of raw gas	kWh/m^3	5.2
Calorific value of purified gas	kWh/m^3	9.8
Calorific value of feed-in gas	kWh/m^3	11.0
Gross digester volume	m^3/h	7,400
Digestate storage volume	m^3/h	6,800
Dry matter content of substrate mixture (incl. recirculate)	%	30.6
Average hydraulic retention time	d	110
Digester organic loading rate	kg VS/m^3 · d	2.5
Raw gas	m^3/a kWh/a	3,652,570 19,021,710
Purified gas	m^3/a kWh/a	1,900,128 18,621,253
Feed-in gas	m^3/a kWh/a	2,053,155 22,581,100

8.1.5 Capital costs of functional units of model plants

Tables 8.9 and 8.10 provide an overview of the estimated capital costs for each of the model plants. The listed items cover the following assemblies (cf. Table 8.5):

- Substrate storage and loading
  - Substrate storage tank
  - Receiving tank
  - Solids loading system
- Digester
- Gas utilisation and control
  - External desulphurisation
  - CHP unit (including peripheral equipment)
  - Where applicable: gas feed-in with gas processing and grid connection (feed-in station and connecting pipeline to natural gas grid)
  - Gas flare
- Digestate storage (including separation, if required).

Table 8.9: Capital costs of functional units of model plants I to V

Capital costs	Unit	I	II	III	IV	V
		30% manure, 70% energy crops			100% energy crops	By-products
		75 kW_{el}	150 kW_{el}	350 kW_{el}	350 kW_{el}	500 kW_{el}
Substrate storage and loading	€	111,703	183,308	291,049	295,653	196,350
Digester	€	72,111	108,185	237,308	259,110	271,560
Gas utilisation and control	€	219,978	273,777	503,466	503,996	599,616
Digestate storage	€	80,506	117,475	195,409	178,509	195,496
Total for assemblies	€	484,297	682,744	1,227,231	1,237,269	1,263,022
Planning and permits/licensing	€	48,430	68,274	122,723	123,727	126,302
Total capital costs	€	532,727	751,018	1,349,954	1,360,996	1,389,324
Specific capital costs	€/kW_{el}	7,090	4,992	3,864	3,888	2,779

Table 8.10: Capital costs of functional units of model plants VI to X

Capital costs	Unit	VI	VII	VIII	IX [a]	X [b]
		100% energy crops 500 kW_{el}	Biowastes 500 kW_{el}	100% energy crops 1,000 kW_{el}	Dry digestion 500 kW_{el}	Gas processing
Substrate storage and loading	€	365,979	173,553	644,810	452,065	644,810
Digester	€	309,746	275,191	593,714	810,000	593,714
Gas utilisation and control	€	601,649	598,208	858,090	722,142	1,815,317
Digestate storage	€	211,098	555,528	371,503	0	371,503
Total for assemblies	€	1,488,472	1,602,480	2,468,116	1,984,207	3,425,343
Planning and permits/licensing	€	148,847	160,248	246,812	198,421	342,534
Total capital costs	€	1,637,319	1,762,728	2,714,928	2,182,628	3,767,878
Specific capital costs	€/kW_{el}	3,264	3,524	2,712	4,362	---

a. using [8-2], [8-3]
b. using [8-6]

8.2 Profitability of the model plants

8.2.1 Revenues

A biogas plant can generate revenues in the following ways:
- sale of electricity
- sale of heat
- sale of gas
- revenues from disposal of digestion substrates
- sale of digestate.

The principal source of revenue for biogas plants, apart from those which feed gas into a grid, is the sale of electricity. As the level of payment and the duration of the entitlement to payment (year of commissioning plus 20 calendar years) are regulated by law, revenues from the sale of electricity can be projected without risk (cf. Section 7.3.2). Depending on the type and quantity of substrates used, the output of the plant and fulfilment of other requirements for payment of bonuses, the tariff for power generation is subject to considerable variation between roughly 8 and 30 ct/kWh. Bonuses are paid for various reasons, including for the exclusive use of energy crops and manure, meaningful use of the heat arising at the plant, use of innovative technology, and compliance with the formaldehyde limits laid down in TA Luft (cf. Section 7.3.3.3). The tariff arrangements are dealt with in detail in Section 7.3.1. The entitlements to EEG payments assumed for the model plants in this section are based on plant commissioning in 2011. Table 8.11 shows the bonuses for which each model plant is eligible.

The situation relating to the sale of heat is significantly more problematic than for electricity. From the very outset, therefore, consideration should be given to potential heat offtakers when the site of the plant is being chosen. In practice it will not be possible to put all the arising heat energy to meaningful use, partly because a certain percentage will be required as process heat and partly because most heat offtakers will have widely differing seasonal heat demands. In most cases, because of the biogas plant's own heat demand, the quantity of heat that can be supplied by the plant will run counter to the heat demand of potential offtakers.

For the model plants it is assumed that 30% of the generated heat energy is put to meaningful use, i.e. in line with Annex 3 EEG, and can be sold for 2 ct/kWh_{th}.

In addition to the heat price, therefore, the plant also receives the CHP bonus of 2.94 ct/kWh_{el} on 30% of the amount of electricity produced.

It may be the plant operator's aim not to convert the biogas into electricity by a CHP process, but to upgrade the gas and feed it into the natural gas grid. Such plants obtain most of their revenues from the gas they sell. As there are no statutory regulations in this case, the gas price must be freely negotiated between the producer and the offtaker. However, EEG makes provision for the possibility of withdrawing the fed-in biogas (biomethane) at another point in the natural gas grid and converting it into electricity under the conditions set out in EEG.

In rare cases, a disposal fee can be charged for substrates used in the plant. However, such a possibility must be carefully examined and, if necessary, contractually secured before being factored into the cost/revenue projections.

Table 8.11: Payment entitlements for model plants based on commissioning in 2011

Model plants	I	II	III	IV	V	VI	VII	VIII	IX
	30% manure, 70% energy crops			100% energy crops	By-products	100% energy crops	Biowastes	100% energy crops	DD
	75 kW_{el}	150 kW_{el}	350 kW_{el}	350 kW_{el}	500 kW_{el}	500 kW_{el}	500 kW_{el}	1,000 kW_{el}	500 kW_{el}
Basic tariff	x	x	x	x	x	x	x	x	x
NawaRo bonus	x	x	x	x	x[a]	x		x	x
Manure bonus	x	x	x		x[a]				
CHP bonus[b]	x	x	x	x	x	x	x	x	x
Air quality bonus					x	x	x	x	x
Av. payment ct/kWh_{el}	23.09	23.09	20.25	17.88	14.08	18.52	11.66	15.93	18.52

a. Payable only for electricity from energy crops and manure (cf. Section 7.3.1)
b. For 30% of the arising quantity of heat

Determination of the value of the digestate depends on many factors. A positive or negative value can be assumed depending on the supply of nutrients in the region. This is because long transport distances may be involved, in which case high transport costs must be expected. Furthermore, the nutrient value of the applied farm fertilisers must be credited to livestock farming. For the cost calculations of the model plants it was assumed that the digestate is made available to crop production at a cost of €0 per tonne. Crop production must cover just the costs of field spreading and is thus able to make the substrates available at lower cost.

8.2.2 Costs

The cost items can essentially be broken down according to the following structure:

- variable costs (of substrates, consumables, maintenance, repairs and laboratory analyses) and
- fixed costs (capital-expenditure-dependent costs – such as depreciation, interest and insurance – and labour costs).

These individual cost items are explained in the following.

8.2.2.1 Variable costs

Substrate costs

Substrate costs can account for up to 50% of total costs. This is particularly likely to be the case for plants that use exclusively energy crops and other related renewable resources. The costs estimated for the various substrates are presented in Table 8.2. The total substrate costs are shown in Tables 8.12, 8.13 and 8.14. As a result of the high storage/conservation losses, which vary from substrate to substrate, the mass to be stored is greater than the mass actually used in the plant.

Consumables

The consumables primarily comprise electricity, ignition oil, lubricating oil and diesel, as well as plastic sheets and sandbags for covering the silage. For gas feed-in to the grid, the consumables also include propane, which is added to the biogas for gas conditioning.

Maintenance and repair

Maintenance and repair costs are estimated at 1–2% of capital costs, depending on the component. More precise data is available for some components, which enables the cost to be calculated as a function of capacity (e.g. CHP unit with gas spark ignition engine: 1.5 ct/kWh$_{el}$).

Laboratory analyses

Professional process control requires laboratory analysis of the digester contents. The model calculations allow for six analyses per digester per year, each costing €120.

8.2.2.2 Fixed costs

Capital-expenditure-dependent costs

Capital-expenditure-dependent costs are made up of depreciation, interest and insurance. The depreciation allowance is component-specific. Depreciation is linear over 20 years for physical structures and over 4–10 years for the installed technical equipment. The tied-up capital is remunerated at an interest rate of 4%. For the purposes of the profitability calculations, no distinction is drawn between equity capital and borrowed capital. The model calculations assume a blanket rate of 0.5% of total capital costs for the cost of insurance.

Labour costs

As the work at a biogas plant is generally performed by permanent employees and as, if the supply of substrate is credited to crop production, there are no particular labour peaks, labour costs can be included in the fixed costs. The required working time is largely made up of the time needed for looking after the plant (control, monitoring and maintenance) and for loading the substrate. The time required for control, monitoring and maintenance is assumed to be a function of the installed capacity, as shown in Figure 9.5 in the chapter entitled 'Farm business organisation' (Section 9.1.3.2).

The time required for loading substrate is calculated as a function of the substrates and technologies used, on the basis of KTBL data. The wage rate is assumed to be €15 per hour.

Land costs

No allowance is made for land costs for operation of the model plants. If the plant is operated as a community plant or commercial plant, additional cost items, such as lease or rent, must also be taken into account.

8.2.3 Cost/revenue analysis

The minimum objective in operating a biogas plant must be to obtain adequate compensation for the capital invested and the labour employed. Any profit over

Table 8.12: Cost-revenue analysis for model plants I to V

Cost/revenue analysis	Unit	I	II	III	IV	V
		30% manure, 70% energy crops			100% energy crops	By-products
		75 kW_{el}	150 kW_{el}	350 kW_{el}	350 kW_{el}	500 kW_{el}
Revenues						
Electricity fed in	kWh/a	601,114	1,203,542	2,794,798	2,800,143	3,999,803
Average tariff	ct/kWh	23.09	23.09	20.25	17.88	14.08
Sale of electricity	€/a	138,809	277,922	565,856	500,730	563,258
Sale of heat	€/a	4,662	8,457	20,151	20,187	27,437
Total revenues	**€/a**	**143,472**	**286,379**	**586,007**	**520,918**	**590,695**
Variable costs						
Substrate costs	€/a	51,761	95,795	226,557	238,068	273,600
Consumables	€/a	17,574	29,387	36,043	42,900	45,942
Repairs and maintenance	€/a	12,900	17,664	57,369	58,174	73,662
Laboratory analyses	€/a	720	720	1,440	1,440	1,440
Total variable costs	**€/a**	**82,956**	**143,566**	**321,408**	**340,582**	**394,643**
Contribution margin	*€/a*	*60,516*	*142,813*	*264,599*	*180,335*	*196,052*
Fixed costs						
Depreciation	€/a	56,328	78,443	110,378	113,768	117,195
Interest	€/a	10,655	15,020	26,999	27,220	27,786
Insurance	€/a	2,664	3,755	6,750	6,805	6,947
Labour	work hrs./d	1.97	3.25	6.11	6.20	6.05
Labour	work hrs./a	719	1,188	2,230	2,264	2,208
Labour	€/a	10,778	17,813	33,455	33,957	33,125
Total fixed costs	**€/a**	**80,424**	**115,031**	**177,582**	**181,750**	**185,052**
Revenues w/o direct costs	*€/a*	*-19,908*	*27,782*	*87,016*	*-1,415*	*10,999*
Overheads	€/a	750	1,500	3,500	3,500	5,000
Total costs	**€/a**	**164,130**	**260,097**	**502,491**	**525,833**	**584,696**
Electricity generation costs	ct/kWh_{el}	26.53	20.91	17.26	18.06	13.93
Profit/loss	**€/a**	**-20,658**	**26,282**	**83,516**	**-4,915**	**5,999**
Return on total investment	**%**	**-3.8**	**11.0**	**16.4**	**3.3**	**4.9**

and above this will also justify the entrepreneurial risk involved. The degree of success that can be expected from operation of the model plants is explained below.

Model I is unable to achieve an operating profit despite the high level of payments received. This is largely attributable to the very high specific capital costs (> €7,000/kW_{el}) of such a small plant.

The specific capital costs of models II and III are significantly lower. The main reason for the profits earned, however, is the manure bonus that these plants receive. On the revenue side, the manure bonus accounts for €47,000 and €66,000, respectively.

The importance of the manure bonus becomes even more apparent from a comparison of plants III and IV, which are of identical capacity. Although the energy-crop plant (IV) has only slightly higher total costs, it is unable to generate a profit as it fails to qualify for the manure bonus, which results in a lower payment for electricity.

Plant V generates only a very small profit. The reason for this is that its electricity is produced mostly from plant-based by-products, with the consequence that the energy crop bonus and manure bonus, to which the plant is basically entitled, are paid on less than 10% of the electricity generated.

The 500 kW energy-crop plant and the 500 kW waste-fuelled plant achieve similarly high profits of roughly €80,000 and €90,000, respectively. However, those profits are of differing makeup. While the fixed costs are at the same level, the energy-crop plant incurs considerably higher substrate costs. On the other hand, it receives a remuneration rate (6.86 ct/kWh$_{el}$) that is boosted by the energy crop bonus, which results in additional revenues of €275,000 per year. Although the waste-fuelled plant receives a lower remuneration rate, it also has very low substrate costs. Profitability could be further increased in this case if disposal revenues could be obtained for the wastes employed.

The profit for plant VIII is lower than for plant VI despite the use of similar substrates. As, under EEG, significantly lower tariffs apply to plants with a capacity over 500 kW, the average tariff for electricity from plant VIII is approximately 14% below that for plant VI. Nor can this be made up for by the associated economies of scale.

The 500 kW dry digestion plant generates a profit of approximately €30,000. Its higher required number of working hours, due to substrate management, and higher fixed-cost charges, are particular reasons why its profit is lower than for wet digestion plant VI, which likewise uses 100% energy crops and has an identical capacity.

Table 8.13: Cost/revenue analysis for model plants VI to IX

Cost/revenue analysis	Unit	VI 100% energy crops 500 kW$_{el}$	VII Biowastes 500 kW$_{el}$	VIII 100% energy crops 1000 kW$_{el}$	IX Dry digestion 500 kW$_{el}$
Revenues					
Electricity fed in	kWh/a	4,013,453	4,001,798	8,009,141	4,002,618
Average tariff	ct/kWh	18.52	11.66	15.93	18.52
Sale of electricity	€/a	743,194	466,606	1,276,023	741,274
Sale of heat	€/a	27,525	27,450	49,900	27,455
Total revenues	**€/a**	**770,719**	**494,055**	**1,325,922**	**768,729**
Variable costs					
Substrate costs	€/a	335,818	40,000	638,409	348,182
Consumables	€/a	51,807	57,504	106,549	50,050
Repairs and maintenance	€/a	78,979	76,498	152,787	81,876
Laboratory analyses	€/a	1,440	1,440	2,880	1,440
Total variable costs	**€/a**	**468,045**	**175,442**	**900,625**	**481,548**
Contribution margin	*€/a*	*302,674*	*318,613*	*425,297*	*287,182*
Fixed costs					
Depreciation	€/a	135,346	143,657	226,328	147,307
Interest	€/a	32,746	35,255	54,299	41,284
Insurance	€/a	8,187	8,814	13,575	10,321
Labour	work hrs./d	7.24	6.31	11.19	9.41
Labour	work hrs./a	2,641	2,304	4,086	3,436
Labour	€/a	39,613	34,566	61,283	51,544
Total fixed costs	**€/a**	**215,893**	**222,291**	**355,485**	**250,456**
Revenues w/o direct costs	*€/a*	*86,781*	*96,322*	*69,812*	*36,725*
Overheads	€/a	5,000	5,000	10,000	5,000
Total costs	€/a	688,937	402,733	1,266,110	737,004
Electricity generation costs	ct/kWh$_{el}$	16.48	9.38	15.19	17.73
Profit/loss	**€/a**	**81,781**	**91,322**	**59,812**	**31,725**
Return on total investment	**%**	**14.0**	**14.4**	**8.4**	**7.1**

Table 8.14: Cost analysis for model plant X

Cost analysis	Unit	X Gas processing
Revenues		
Feed-in gas	m³/a kWh/a	2,053,155 22,581,100
Purified gas	m³/a kWh/a	1,900,128 18,621,253
Raw gas	m³/a kWh/a	3,652,570 19,021,710
Variable costs		
Substrate costs	€/a	638,409
Consumables	€/a	361,763
Repairs and maintenance	€/a	61,736
Laboratory analyses	€/a	2,880
Total variable costs	**€/a**	**1,064,788**
Contribution margin	€/a	-1,064,788
Fixed costs		
Depreciation	€/a	267,326
Interest	€/a	75,358
Insurance	€/a	18,839
Labour	work hrs./d	11.75
Labour	work hrs./a	4,291
Labour	€/a	64,358
Total fixed costs	**€/a**	**425,881**
Revenues w/o direct costs	€/a	-260,897
Overheads	€/a	10,000
Costs of supplying feed-in gas	**€/a**	**1,500,670**
Specific costs of feed-in gas	**€/m³ ct/kWh**	**0.73 6.65**
of which:		
costs of supplying purified gas	**€/a**	**1,334,472**
Specific costs of supplying purified gas	**€/m³ ct/kWh**	**0.70 7.17**
of which:		
costs of supplying raw gas	**€/a**	**1,030,235**
Specific costs of supplying raw gas	**€/m³ ct/kWh**	**0.28 5.42**

As there is presently still no market price available for biogas (biomethane) fed into the grid, only the costs are given for the gas feed-in plant rather than a cost/revenue analysis. The costs given for the individual items relate to the entire process, including feed-in to the natural gas grid. The table also presents the total costs and specific costs of the supply of raw gas (interface at biogas plant) and purified gas (interface at biogas processing plant). The prices are not directly comparable, because different quantities of gas and energy are made available at the respective interfaces. For example, before being fed in to the grid, the gas is mixed with propane, which is significantly cheaper based on energy content than the produced biogas. This results in lower specific costs for the feed-in gas than for the purified gas (based on energy content).

8.3 Sensitivity analysis

The purpose of the sensitivity analysis is to show which factors have the greatest influence on the profitability of a biogas plant. Table 8.15 and Table 8.16 indicate the extent to which the profits change when the respective factors are changed by the given amounts.

The greatest impact is from changes to gas yield, methane content and electrical efficiency as well as from changes to substrate costs, especially in plants using a high proportion of energy crops. The importance of the change in acquisition costs is all the greater, the higher the specific acquisition costs of the plant. In other words, this has a greater effect on small plants than on larger plants. There are less strong impacts from changes to the following factors: working hours, maintenance and repair costs and the sale of heat. Especially with regard to the sale of heat, however, the situation would be different if a heat strategy could be put in place that made considerably more use of the heat and perhaps also achieved higher prices.

Similarly, a very significant impact results from changing the electricity tariff by 1 ct/kWh, although, in practice, it is barely possible to influence the tariff. The example illustrates, however, what influence the loss of the air quality bonus could have: it would drive Plants IV, V and VIII into loss-making territory.

In the case of plant I, the improvement of a single factor would not lead to it making a profit. An operating profit would be achieved only if a 10% reduction in acquisition costs were combined with a 5% increase in gas yield.

Plants II and III have greater stability thanks to their lower specific capital costs and higher tariffs. Even if certain parameters change for the worse, they will continue to make a profit. The same applies to the waste-fuelled plant (VII), although, in that case, this is largely due to the very low substrate costs.

Table 8.15: Sensitivity analysis for model plants I to V

Sensitivity analysis Change in profits in €/a	I	II	III	IV	V
	30% manure, 70% energy crops			100% energy crops	By-products
	75 kW_{el}	150 kW_{el}	350 kW_{el}	350 kW_{el}	500 kW_{el}
Change in acquisition costs by 10%	6,965	9,722	14,413	14,779	15,193
Change in substrate costs by 10%	5,176	9,580	22,656	23,807	27,360
Change in gas yield/methane content/ electrical efficiency by 5%	6,784	13,793	23,309	21,953	33,358
Change in required working hours by 10%	1,078	1,781	3,346	3,396	3,312
Change in maintenance and repair costs by 10%	1,290	1,766	5,737	5,817	7,366
Change in electricity tariff by 1 ct/kWh	6,011	12,035	27,948	28,001	39,998
Change in sale of heat by 10%	1,166	2,114	5,038	5,047	6,859

Table 8.16: Sensitivity analysis for model plants VI to IX

Sensitivity analysis Change in profits in €/a	VI 100% energy crops 500 kW_{el}	VII Biowastes 500 kW_{el}	VIII 100% energy crops 1,000 kW_{el}	IX Dry digestion 500 kW_{el}
Change in acquisition costs by 10%	17,628	18,772	29,420	19,891
Change in substrate costs by 10%	33,582	4,000	63,841	34,818
Change in gas yield/methane content/ electrical efficiency by 5%	31,465	17,368	43,049	31,381
Change in required working hours by 10%	3,961	3,457	6,128	6,436
Change in maintenance and repair costs by 10%	7,898	7,650	15,279	6,174
Change in electricity tariff by 1 ct/kWh	40,135	40,018	80,091	40,026
Change in sale of heat by 10%	6,881	6,862	12,475	6,864

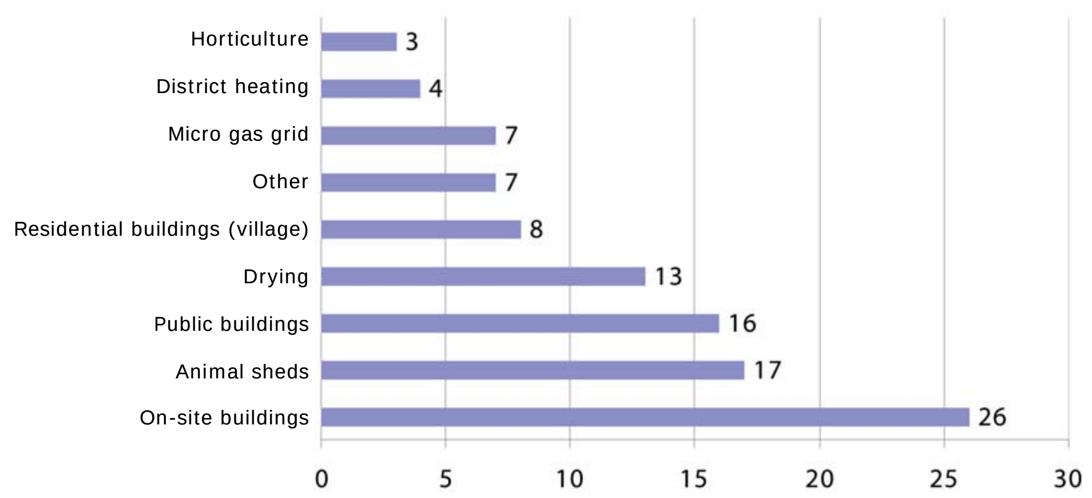

Figure 8.1: Uses of waste heat from biogas plants operating with a CHP process [8-7]

8.4 Profitability of selected heat utilisation pathways

Alongside the revenue from electricity, utilisation of the heat from the CHP process is increasingly becoming a key factor in the economic success of a biogas plant. Whether or not heat utilisation can make a significant contribution to that success will depend primarily on how much heat can be sold to offtakers. The foundation for the economic advantages of heat utilisation is laid by the CHP bonus under the Renewable Energy Sources Act [8-1].

As part of a national competition promoted by FNR (Agency for Renewable Resources) on model solutions for future-oriented biogas plants, KTBL analysed data from 62 biogas plant in 2008. The results show that the amount of heat utilised outside the biogas process averages only 39% in relation to the amount of electricity generated. Of the plants analysed, 26 used the heat in on-site buildings (workshop, office), while 17 plants used it to heat animal sheds; 16 plants supplied heat to public buildings such as hospitals, swimming pools, schools and kindergartens; and 13 plants used the heat for drying (cf. Figure 8.1).

Residential buildings, micro gas grids, district heating and horticulture enterprises are of minor importance as heat offtakers, as such types of heat utilisation are heavily dependent on the chosen site of the biogas plant.

The following sections will examine and explain the profitability of selected heat utilisation pathways. Calculation of the revenues from CHP under EEG 2009 is based on plants commissioned in 2011, as in the case of the model plants. As the bonuses under EEG are also subject to an annual degression rate of 1%, the level of the CHP bonus for 2011 is €0.0294 per kWh, taking account of the restrictions specified in the Positive List and Negative List.

8.4.1 Utilisation of heat for drying

8.4.1.1 Grain drying

Grain drying is only a time-limited option for utilising the waste heat from biogas. Grain is dried in order to improve its storability. On average, around 20% of the crop with a grain moisture content of 20% must be dried to a residual moisture of 14%. This is often done with the aid of batch dryers or mobile dryers. The benefit of grain drying using CHP waste heat is that the heat is used in summer, when there is less demand from other heat users, such as for heating buildings.

The calculations below show whether drying with CHP waste heat is economically advantageous when compared with the use of fossil fuels.

Assumptions:
- grain is dried by batch dryer;
- 20% of the crop is dried from a residual grain moisture of 20% down to 14%;
- the quantity harvested is 800 t/a – so the quantity for drying is 160 t/a;
- the drying plant operates for 20 hours per day for a total of 10 days per year.

Table 8.17: Cost/revenue analysis of grain drying using biogas or heating oil as the heat carrier

Parameter	Unit	Grain drying using:	
		biogas	heating oil
Revenues			
CHP bonus	€/a	470	0
Costs			
Total variable costs	€/a	224	1,673
Total fixed costs	€/a	1,016	1,132
Total labour	€/a	390	390
Total overheads	€/a	150	150
Total costs	**€/a**	**1,780**	**3,345**
Specific costs			
Costs per tonne of saleable grain	**€/t**	**1.66**	**4.24**

To dry a quantity of grain of 160 t/a in the specified period, the required output from the heat exchanger is calculated as 95 kW. Therefore, 18,984 kWh of heat energy will be required annually.

If, for example, the heating work of model plant III is assumed at 3,364,804 kWh/a, then drying 160 t of grain will utilise only about 0.6% of the heat generated by the biogas plant. The amount of energy used for drying is equivalent to that from roughly 1,900 litres of heating oil.

Table 8.17 contrasts the costs and revenues of drying grain using biogas and heating oil as heat carrier.

If a heating oil price of €0.70/l is taken as a basis, approximately €1,318 can be saved per year by substituting heating oil with biogas. This is the reason why the variable costs are so much lower for drying with biogas as the heat carrier than when using heating oil. When the CHP bonus for the equivalent quantity of

Table 8.18: Cost/revenue analysis of grain-drying methods utilising waste heat from biogas CHP unit without receipt of CHP bonus ([8-9], modified on the basis of [8-8])

	Unit	150 kW_{el} Mixed-flow dryer	500 kW_{el} Mixed-flow dryer	500 kW_{el} Feed-and-turn dryer	150 kW_{el} Mobile drying	500 kW_{el} Mobile drying
Assumptions						
Instead of a heat generator (heating oil), a heat exchanger is used to transfer heat from the CHP unit to the drying plant						
Useful amount of heat from biogas plant after deduction of digester heating	MWh/a	1,136	3,338	3,338	1,136	3,338
Proportion of utilised waste heat from biogas plant[a]	%/a	9	9	13	9	9
Waste heat utilised	kWh	102,240	300,420	433,940	102,240	300,420
Amount of product (grain) processed	t FM/a	1,023	3,009	4,815	1,023	2,972
Installed heat capacity	kW	88	283	424	88	283
Total capital costs[b]	€	48,476	93,110	140,010	25,889	64,789
Costs						
Capital costs and maintenance	€/a	4,966	10,269	15,468	3,025	8,182
Electricity	€/a	844	1,878	2,450	738	1,633
Labour	h/a	260	260	293	326	456
	€/a	3,658	3,658	4,116	4,573	6,402
Insurance	€/a	251	479	721	134	332
Total costs	€/a	9,979	16,544	23,048	8,796	17,005
Revenues without CHP bonus						
Increase in value from drying the products[c]	€/a	13,105	38,550	61,684	13,105	38,076
CHP bonus	€/a	0	0	0	0	0
Total revenues		13,105	38,550	61,684	13,105	38,076
Profit without CHP bonus						
Profit	€/a	3,126	22,006	38,636	4,309	21,071
Break-even point	€/t FM	3.06	7.31	8.02	4.21	7.09

a. Drying period: July and August, during which time mixed-flow drying and mobile drying would utilise 50% of the thermal output of the biogas plant, while feed-and-turn drying would utilise 75% of the thermal output of the biogas plant.
b. Investment in dryer, so that eligibility criteria from Annex 3 EEG: additional costs amount to €100 per kilowatt of installed thermal capacity are met
c. Increase in value obtained as a result of improved storability and better marketing opportunities: €10/t FM.

electricity of approx. €470 is added, grain drying using CHP waste heat results in a cost advantage of €2,035 per year. With reference to the harvested quantity, the drying costs using biogas amount to €1.66 per tonne of saleable grain as compared with €4.24 per tonne using heating oil.

If grain drying is the sole drying method used, it may be necessary to examine and satisfy eligibility criterion I.3 for entitlement to the CHP bonus under EEG 2009: '…the additional costs arising from the supply of the heat, which amount to at least 100 euros per kilowatt of heat capacity.' Thus, additional capital expenditure may be required for this drying method before entitlement to the CHP bonus is obtained. This, however, can increase the costs to €3,023/a, thereby almost cancelling out the cost advantage of utilising heat from biogas and increasing the specific drying costs with biogas to €3.24 per tonne of saleable grain as compared with €4.24 per tonne using heating oil.

As the calculation example shows, using such a small proportion of the total quantity of waste heat for grain drying as the only form of heat utilisation is not economically worthwhile. It needs to be examined whether grain drying can be employed as a seasonal option on top of other heat utilisation strategies.

Table 8.19: Cost/revenue analysis of grain-drying methods utilising waste heat from biogas CHP unit with receipt of CHP bonus ([8-9], modified on the basis of [8-8])

	Unit	150 kW_{el} Mixed-flow dryer	500 kW_{el} Mixed-flow dryer	500 kW_{el} Feed-and-turn dryer	150 kW_{el} Mobile drying	500 kW_{el} Mobile drying
Revenues with CHP bonus						
Increase in value from drying the products[a]	€/a	13,105	38,550	61,684	13,105	38,076
CHP bonus	€/a	2,576	7,805	11,274	2,576	7,805
Total revenues		15,681	46,355	72,958	15,681	45,881
Profit with CHP bonus						
Profit	€/a	5,702	29,811	49,910	6,885	28,876
Break-even point	€/t FM	5.57	9.91	10.37	6.73	9.72

a. Power-to-heat ratio of 150 kW plant: 0.857; power-to-heat ratio of 500 kW plant: 0.884

Table 8.20: Heating oil saving for grain-drying methods utilising waste heat from biogas CHP unit

	Unit	150 kW_{el} Mixed-flow dryer	500 kW_{el} Mixed-flow dryer	500 kW_{el} Feed-and-turn dryer	150 kW_{el} Mobile drying	500 kW_{el} Mobile drying
Substitution of fossil fuels						
Amount of heating oil saved[a]	l/a	14,700	34,700	51,410	11,760	34,235
Heating oil costs saved[b]	€/a	10,290	24,290	35,987	8,232	23,965

a. Amount of heating oil saved compared with use of heating oil as fossil-fuel heat carrier for drying. Efficiency of heating oil air heater: 85%
b. Heating oil price: €0.7/l

However, if offtakers are found for large quantities of heat for drying (e.g. for contract drying), then profitability may be achievable, as is demonstrated by example calculations in [8-8].

It is assumed that 9% of the available heat from a biogas plant can be utilised on about 50 days during the summer months of July and August in Germany. It is further assumed that the additional costs of making the heat available will amount to at least €100 per kilowatt of heat capacity, which means that the CHP bonus can be included among the revenues.

Table 8.18 and Table 8.19 show that, under these conditions, even a small biogas plant (150 kW) is capable of making an appreciable profit, assuming that the increase in value of the grain as a result of improved storability and better marketing opportunities is valued at €10/t FM. Mere inclusion of the CHP bonus, however, is not enough to reach break-even point with the drying variant (see also Table 8.19).

If heating oil is replaced by biogas as the heat carrier, the saving in heating oil costs alone will cover the total costs of the drying variant using CHP waste heat (see Tables 8.18 and 8.20).

In a comparison of the two methods of drying, the expected profit from mobile drying is comparable to that from mixed-flow drying, despite capital costs being as much as 55% lower. This is attributable to the higher labour costs for mobile drying (e.g. through changing of trailers), the labour costs being 25% or 75% higher depending on the size of plant.

8.4.1.2 Digestate drying

Digestate drying was assessed as being a method of utilising the heat from CHP generation that is worth supporting, and was therefore included in the Positive List in EEG 2009 (digestate is referred to as 'fermentation residues' in EEG). This heat utilisation option makes the plant operator eligible to receive the CHP bonus if the product of processing is a fertiliser. The effect of this form of heat utilisation on the profitability of a biogas plant will be positive only if there are no other profitable heat utilisation options available, as the revenues will usually be limited to the CHP bonus. It will not be possible to reduce the costs of fertiliser application or to add value to the digestate by the drying process unless there are utilisation or marketing strategies in place for the product of drying.

8.4.2 Heat utilisation for greenhouse heating

Greenhouses can consume large quantities of heat for long periods of time. This represents a reliable revenue stream while at the same time resulting in low heat supply costs for the greenhouse operator. The example described below presents the supply of heat for various crop cultivation regimes and two different sizes of greenhouse.

With regard to the growing of ornamental plants, a distinction is drawn between three crop-specific temperature ranges: 'cool' (< 12 °C), 'tempered' (12–18 °C) and 'warm' crop cultivation management (> 18 °C).

For an analysis of profitability, the example looks at a biogas plant with an installed electrical capacity of 500 kW. It is assumed that a total of 30% of the heat from the CHP unit is required for heating the digester. Consequently, around 70% of the generated heat, i.e. some 3,200 MWh thermal per year, is available for heating purposes.

Table 8.21 contrasts the heat demand of the various cultivation regimes for greenhouses with an area under glass of 4,000 m² and 16,000 m² respectively, utilising the waste heat potential of a 500 kW_{el} CHP unit, as a function of cultivation regime and greenhouse size.

The calculation example assumes that heat is supplied from CHP waste heat instead of from heating oil. The CHP waste heat covers the base load, with heating by heating oil covering the peak load. The corresponding costs of meeting the peak load are taken into account in the calculations (cf. Table 8.22).

The heat is extracted from the CHP unit in the form of hot water and is routed to the greenhouse through a local heating pipe.

Although greenhouse heating is listed as one of the heat utilisation categories in the Positive List of EEG 2009, no entitlement to payment of the CHP bonus can be obtained unless such heating replaces the same amount of fossil-fuelled heat and the additional costs of heat supply amount to at least €100 per kW of heat capacity.

In the calculation example below, the additional costs of heat supply from the biogas plant exceed the €100 per kW of heat capacity required by EEG, which means that payment of the CHP bonus can be included among the revenues.

It is further assumed that the biogas plant operator sells the heat at €0.023/kWh_{th}. In addition to the CHP bonus, therefore, there are extra revenues from the sale of heat.

For a greenhouse operator engaged in 'cool' ornamental horticulture, there is a cost advantage of €10,570 or €78,473 per year as compared with heating with heating oil alone, assuming the above-mentioned heat costs of €0.023/kWh and despite the additional capital costs of the heat supply pipe (cf. Table 8.22).

The calculations are based on a heating oil price of 70 cents/l.

For the 'tempered' and 'warm' cultivation regimes, the potential savings rise to as much as 67% through the increased sale of heat with only a slight increase in fixed costs.

8.4.3 Heat utilisation for municipal local heating scheme

The basis for the use, upgrading and new build of heat networks is created by the statutory framework in the form of the amended Renewable Energies Heat Act, the Law on Cogeneration and the associated support possibilities provided by states and districts as well as by subsidised loans.

Table 8.23 presents a planning example with the key parameters for a municipality that is to be supplied with heat. It compares the supply of heat from a wood chip furnace with that from the waste heat from

Table 8.21: Annual heat demand of greenhouses and utilisation of waste heat potential of a 500 kW_{el} biogas plant for different cultivation regimes and greenhouse sizes

Cultivation regime	Cool ornamental horticulture		Tempered ornamental horticulture		Warm ornamental horticulture	
Area under glass [m²]	4,000	16,000	4,000	16,000	4,000	16,000
Heat required for heating [MWh/a]	414	1,450	1,320	4,812	1,924	6,975
Utilised waste heat potential of a 500 kW_{el} biogas plant [%]	13.3	46.4	42.2	100	61.6	100

Table 8.22: Comparison of heat supply costs for heating by heating oil and by waste heat from biogas CHP unit with reference to the example of two sizes of greenhouse with 'cool' cultivation regimes

		Area under glass			
		4,000 m²		16,000 m²	
		Supply of heat from			
	Unit	Heating oil	Biogas	Heating oil	Biogas
Capital costs	€	86,614	141,057	155,539	216,861
Total variable costs (repairs and fuel costs)	€/a	37,770	22,235	129,174	45,105
Total fixed costs (depreciation, interest, insurance)	€/a	7,940	2,930	14,258	19,879
Total labour	€/a	390	390	390	390
Total overheads	€/a	500	500	500	500
Total costs	€/a	46,625	36,055	144,348	65,874
Difference between oil and biogas heating	€/a	10,570		78,473	
Saving from biogas versus oil heating	%	22.7		54.4	

Table 8.23: Assumptions and key parameters for heat supply in a municipal local heating scheme with base load met by biogas CHP waste heat and wood chip furnace [based on 8-10]

	Unit	Biogas CHP waste heat	Wood chips
Houses	Number	200	
School	Pupils	100	
Administration/office building	Employees	20	
Total heat demand	**MW**	**3.6**	
Heat demand from biogas/wood chips	MW/a	1.1	
Heat demand from oil-fired boiler	MW/a	2.6	
Total heat	**MWh/a**	**8,000**	
of which biogas waste heat/wood chip heat	**MWh/a**	**5,600**	**5,200**
Network length	m	4,000	
Annual heat demand	kWh/a	6,861,000	

Table 8.24: Required capital costs and heat supply costs for the municipal local heating scheme as a function of the selling price of the biogas CHP waste heat [8-10]

	Unit	CHP waste heat			Wood chips
Selling price of biogas waste heat	ct/kWh	1	2.5	5	
Required capital costs[a]	€		3,145,296		3,464,594
Required capital costs of heat distribution[b]	€	2,392,900			
Costs	€/a	571,174	655,594	796,294	656,896
Heat supply costs	ct/kWh	8.32	9.56	11.61	9.57
of which costs of heat distribution[b]	ct/kWh	3.17			

a. These include: heating and utility building, plant components for peak load supply (oil-fired boiler and oil storage facility), common plant components (buffer store, electrical installations, instrumentation and control systems, sanitation, ventilation and air-conditioning systems), district heating network, incidental construction costs (planning and approval). Additional capital costs of a biomass furnace and biomass storage are included for the wood chips.
b. The biogas plant is not included in the capital costs. The heat is transferred to the network described here downstream of the CHP unit.

Table 8.25: Qualitative classification of various heat utilisation pathways

Heat utilisation pathway/ heat sink	Capital costs	Heat output quantity	Heat supply (continuity of heat output)	CHP bonus	Substitution of fossil fuels
Drying					
- Grain	++/+	0	-	(-)[a]	+
- Digestate	0	++	++	+	-
- Wood chips	+/0	+	0	(-)[a]	0/-
Heating					
- Horticulture	+/0	++	0[b]	+	++
- Residential buildings	-	+/++[c]	+[d]	+	++
- Industrial buildings	+/0	+/++[c]	++[d]	+	++
- Animal sheds	+/0	0[e]	0	+	+
Cooling					
- Dairies	-[f]	++	++	+	++
- Milk precooling	-[f]	0	+	-	-

++ = very good/in case of capital costs: very low
+ = good/in case of capital costs: low
0 = average/in case of capital costs: neutral
- = poor/in case of capital costs: high or very high

a. Entitlement to the CHP bonus is achieved only if additional costs arising from the supply of heat amount to at least €100 per kilowatt of heat capacity.
b. It may be the case that heat is supplied only in the winter months, with the amount of heat varying greatly depending on the temperature level of the cultivation regime and the size of the greenhouse
c. Depends on the makeup of the buildings being heated. Of interest for dense housing developments with poorly insulated buildings and for large-scale municipal and commercial consumers.
d. For covering the base load only. Peak load must be met by other energy sources.
e. Amount of heat output restricted by upper heat limits in EEG Annex 3
f. Capital costs of absorption refrigerator

a biogas plant. It is assumed that the base load (about 30% of demand) is met by a wood chip boiler or biogas plant, with the peak load being met by an oil-fired boiler (about 70% of demand). The municipality consists of 200 houses, a school and an administrative building. The heat is distributed to the consumers through a hot water heat network. As the municipality's heat demand amounts to 3.6 MW, the wood chip boiler or biogas plant must be designed for a heat capacity of at least 1.1 MW.

Capital costs of €3.15 million (biogas) or €3.46 million (wood chips) can be assumed for the examples. The capital costs of the biogas plant are not counted as part of the heat generation costs, which explains why the capital costs are lower. At around 70%, the local heating pipeline (with main pipeline) as well as the transfer stations and house connections account for most of the capital costs. The calculations assume average required capital costs of €410/m for the local heating pipeline, of which only about €50 to 90/m is attributable to heating pipe materials.

Depending on the selling price of the CHP waste heat from biogas, the heat production costs are 8.3 to 11.6 ct/kWh. The heat distribution costs alone account for 3.17 ct/kWh. Another important cost item is the supply of heating oil (for peak load). It is apparent that, in this example, the waste heat from the biogas CHP unit can cost about 2.5 ct/kWh for it to be able to compete with a wood chip heating plant.

8.5 Qualitative classification of various heat utilisation pathways

An overview of the qualitative classification of various heat utilisation pathways is given in Table 8.25.

8.6 References

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Source: Tannhäuser Ingenieure

Farm business organisation

9

The decision to establish biogas as a production branch at a farm or farming collective, or to convert a farm to biogas, can essentially be founded on the following principal arguments:

- establishment of a new branch of business to broaden the production base;
- safeguarding of income by taking advantage of the price guarantee for biogas electricity;
- source of liquid assets throughout the business year;
- market-independent utilisation of land;
- recovery of energy from primary products and by-products;
- reduction of emissions and odours from the storage and application of farm fertiliser;
- improved availability to crops of the nutrients from farm fertiliser;
- self-sufficiency in terms of energy supply;
- enhanced image of the farm.

Before the decision to produce biogas is taken, the following options for the production and use of biogas should be examined and weighed up. The decision will depend also on an individual's willingness to take risks (cf. Figure 9.1).

Option 1: supply of substrate to an existing or new biogas plant; low risk in terms of capital expenditure and operation of the biogas plant, but lower share of the value added from biogas.

Option 2: construction of an on-farm or community biogas plant, either for converting the biogas into electricity at the plant or for selling the biogas to a gas processor, for example; high risk in terms of capital expenditure and operation of the biogas plant, but high share of the value added from biogas.

Option 1 is comparable with the production of commercial crops. However, particularly with regard to the production, say, of maize silage, it should be noted that the dry matter content of the fresh mass of around 30–40%, compounded by the max. 24-hour shelf life of the silage after removal from storage, makes for limited transportability. At best, therefore, it will be possible to serve a regional market, assuming the silo is located on the producer's premises.

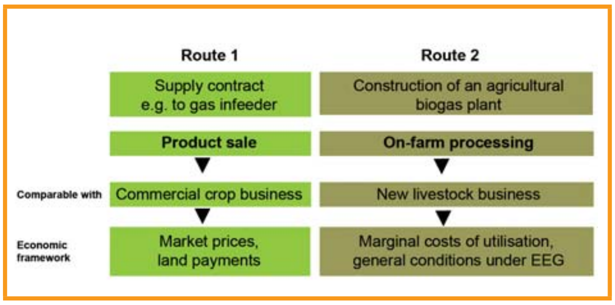

Figure 9.1: Options open to the farmer for biogas production

Where the crop is sold directly from the field, as is often the case in southern Germany, the silage capacity will be on the user's premises, i.e. at the biogas plant. In this case, too, the market will only be regional, because of the required transport capacity.

Regionalisation is further encouraged by the transport costs involved in utilising the digestate, which is mostly stored at the location of the biogas plant. From the standpoint of the biogas plant operator, long-term contracts to meet the relatively constant demand for substrate are desirable. Especially at marginal locations or where yields are liable to variation, this can be a problem for the farmer as far as fulfilment of the contract is concerned.

Option 2, on the other hand, can be compared with the construction of a livestock facility. 'Product processing' takes place on the farm, the aim being to generate a profit from processing, to broaden the production base and to make an investment in the future. This requires additional capital expenditure of €6,000 to 8,000/ha, with both the capital and the land being tied up for a long time, about 20 years. A further aim is to earn an appropriate return on the capital in-

Table 9.1: General conditions to be considered for substrate planning

Substrate planning	General conditions
• Farm fertiliser available (with details of DM and VS)	• Storage capacity available (for silage, digestate)
• Agricultural residues arising on the farm	• Heat demand of farm or nearby offtakers (quantities, seasonal cycle)
• Land availability, yields and costs of growing energy crops	• Feed-in points for heat and power • Usable building stock
• Residues from the food and feed industries[a]	• Land available for utilisation of digestate • Compliance with the Ordinance on Biowastes • Transport distances for input substrates and utilisation of digestate • Calculation of the feed-in tariff payable for the use of specific substrates[a]

a. The requirements set out in EEG (2009) for calculating the level of feed-in tariffs must be taken into account here

vested. This must be examined with the aid of a cost/revenue analysis (cf. Section 8.2.3).

Especially after the amendment of the Renewable Energy Sources Act (EEG) in 2009, the construction of an agricultural biogas plant is predicated on the availability of farm fertiliser, an ability to make meaningful use of the heat generated, the area of land needed to supply the substrate, and the potential for utilisation of the digestate.

More specifically, it is necessary to determine the arising volume of farm fertiliser and the dry matter (DM) content (guide value 0.15 ... 0.2 kW per livestock unit). If the DM content is known, the arising volume of manure can be calculated on the basis of guide values from, for example, the state agricultural research institutes or KTBL. It should be borne in mind that a single manure sample will often produce an unreliable value.

In addition, it is necessary to determine the arisings of agricultural residues (such as fodder residues, top layers of silos, etc.) as well as the availability of any purely plant-based by-products for use as possible self-financing substrates, with regard to both timing and volume, bearing in mind the distances involved in transport. Under the tariff arrangements in EEG, the DM content of purely plant-based by-products is of great significance, because, for the power yield from such substances, a fixed amount of power based on the fresh mass input does not qualify for the NawaRo bonus (cf. Section 7.3.3.2).

Where the digestion of wastes is being considered as an option, the points to examine are the availability of biowastes, transport distances, any requirements relating to conservation of the wastes, concerns over digestion biology and legal issues, and the possible need for hygienisation.

As far as the use of field crops is concerned, when planning an agricultural biogas plant, farmers should be clear about which areas of their land they are able or intend to use for biogas, with what yields and what types of crops. As a rough estimate, 0.5 ha/kW$_{el}$ can be assumed as typical. With due consideration for questions of crop rotation and labour management, preference should be given to high-yield crops with low costs per unit of organic dry mass or per cubic metre of methane. Nevertheless, it may make business sense to grow other whole-crop silages rather than maize if this can balance out the labour peak during maize harvesting and allow the fields to be cleared sooner, for example for sowing oil-seed rape.

Using the entire area of the farm to grow basal feed for cattle and to produce substrate for biogas does not usually make sense, as it is then no longer possible to participate in the market. Furthermore, approaches such as these are inappropriate because of the need for crop rotation on arable farms.

Buying in biomass is common practice where sufficient substrate cannot be produced on the farm's own land. Even where farmers try to enter into long-term contracts in such cases – often with a price adjustment clause – the level of material and economic security for the biogas plant is lower. The construction of additional plants in the region, or changes in agricultural prices, as happened in 2007/08, can have a significant effect on the regional market. Table 9.1 summarises the general conditions that need to be taken into consideration for substrate planning.

When deciding on the size of biogas plant to be built, it is necessary to take into consideration not only the supply of substrate, potential utilisation of digestate and quantity of heat that can be put to meaningful use, but also technical, legal, administrative und tariff-related issues. The desired size of biogas plant is sometimes determined without reference to the specific nature of the site in question (heat demand, use of biogas slurry, sizes and structures of farms, etc.) or to the availability of substrate or matters of labour management. However, this can give rise to considerable economic and structural problems and is not recommended.

To sum up, it should be borne in mind that the following factors are particularly important in relation to the actual integration of a biogas plant into an agricultural enterprise:

- **Land requirements** and commitment periods (20 years), although these may also be influenced by the buying-in of substrate, for example.
- **Fertilising regime:** possible increase in the volume of material for spreading on fields and in the quantity of nutrients in the farming cycle.
- **Use of fixed assets:** possibility of making use of existing silos, slurry stores, ...
- **Labour management**: this should take account of the production, harvesting and storage or procurement of raw materials (substrates), operation of the plant, including the processing/loading of substrates, process monitoring, technical support, maintenance, rectification of faults and damage, administrative tasks and field spreading of digestate (example: production, harvesting and storage of grain: 6–8 h/ha as compared with maize silage: 13–15 h/ha).

To cushion the risk, the plant can be built jointly with a partner farm. For this purpose, one option may be to set up a private partnership to generate the basic revenues from energy crops, manure and other substances, such as fats (cf. Section 9.2.2).

The most important factors influencing the restructuring of a farm are set out in the following.

9.1 Farm restructuring – future prospects and approaches to optimisation

Planning and construction of the plant requires the farmer's participation in a variety of ways. The following list provides an overview of the farmer's key decisions and activities during planning of the biogas plant and its integration into the farm:

- site selection;
- clarification of the electrical connection for feeding the generated power into the grid, including the often required construction of a new transformer station;
- clarification of how the plant will be integrated into the farm on the heat side;
- clarification of how the plant will be integrated on the substrate side;
- licensing procedure (preparation of permit application);
- expert assessments (soil report for the plant site, structural analysis for tanks and new structures, health and safety plan for the construction site, inspection by technical inspection agency, ...);
- any required expansion of storage space for additional digestate from co-substrates;
- site facilities and equipment (outdoor lighting, fencing, signage, paths, water pipes, compensatory planting, ...);
- heating of the plant and fault clearance during the start-up phase and support services for the first six months of operation.

9.1.1 Selection of an appropriate plant site

All of the key parameters for site selection are shown in Figure 9.2 below. The larger the plant, the more important the question of optimum plant location becomes. The opportunities for distributing and utilising the energy products are particularly important (cf. Section 11.2.2).

It should also be borne in mind that transporting heat makes economic sense over short distances only, and that transporting electricity in the low-voltage range can lead to significant line losses and hence to a lower rate of economic return.

Another factor relevant to site search and selection is the extent to which the transport of substrate and digestate is feasible for the planned size of plant (cf. Section 11.2.2). It also needs to be clarified whether the necessary quantities of substrate of appropriate quality will be available at the location over the longer term. Furthermore, the approval regulations require that a certain distance be maintained from livestock facilities, residential buildings and sensitive water resources. The plans should make allowance for future expansion phases.

In addition to administrative planning parameters, it is also necessary in site search and selection to take account of geological factors, such as groundwater level or soil characteristics (soil type, rock content, etc.). Opportunities for financial support from authorities at local or regional level may be of interest in helping to finance a plant.

9.1.2 Impact of biogas plant on crop rotation

The production of biomass may necessitate adjustments to the system of crop rotation. The priority in this case is on growing crops for gas production as

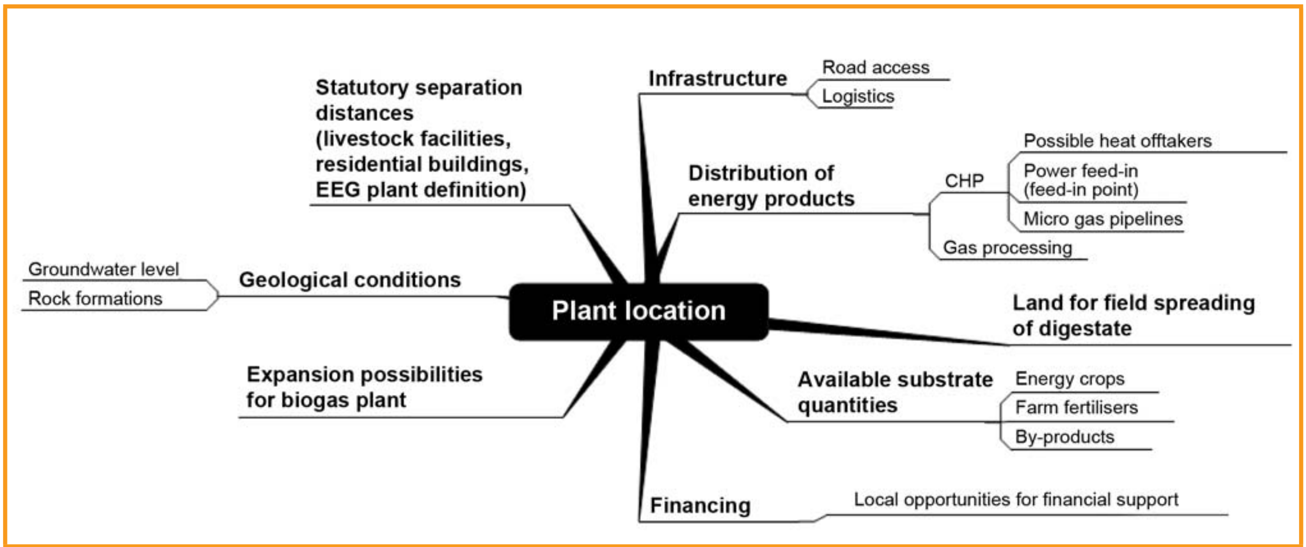

Figure 9.2: Parameters influencing the choice of plant location (CHP: combined heat and power)

close to the farm as possible in order to minimise transport costs. However, this objective cannot always be met, depending on the size of plant and quantity of substrate (energy crops) required as well as for reasons of crop rotation. For a plant operator who also keeps pigs, for example, it may well make economic sense not to feed the winter barley grown on the farm's own land to the pigs, but instead to harvest the barley at an earlier date, when at the doughy stage, for use as whole-crop silage to produce biogas. The pigs will then instead be fed with bought-in feed barley. The early barley harvest means that, in favourable locations, it will then be possible to grow silage maize as a second crop or aftercrop using early varieties. A side-effect of growing maize as a main crop is the possibility of putting the arising digestate to environmentally sound use for crop cultivation over a longer period of time.

Changing the cropping sequence to focus on biogas production can result in almost year-round greening of arable land, something that has a positive effect in terms of nitrogen exploitation.

Depending on soil moisture content at the time of the maize silage harvest, driving on the fields can have a detrimental impact on soil structure if soil conditions are unfavourable, especially when harvesting second-crop maize.

Both from an agricultural standpoint and also in terms of digestion biology, it has proved beneficial to use a broad mix of substrates in biogas plants. Growing whole-crop cereal (WCC) silage leads to the fields being cleared earlier and allows oil-seed rape, for example, to be sown on time. Maize is a very high-yielding crop and can make good use of digestate in the spring. The use of cereal grain as a means of controlling gas production, for example, is also to be recommended. In addition, cereal grain can be bought in to compensate for fluctuations in the yield of substrates grown on the farm, thereby possibly avoiding the need for substrate to be transported over long distances or in large quantities.

Table 9.2: Required land, tied-up capital and required working time for various production branches

	Grain 65 dt/ha	Maize 400 dt/ha	153 DC (8000 l)	BGP 150 kW	BGP + 150 DC
Required land [ha]	1	1	118 ha 0.77 ha/cow	79	183 (67 ha BGP)
Tied-up capital [€/ha]	876	2,748	4,660	6,126	5,106
Required working time [work hrs./ha]	9.3	15.5	65.6	31.1	66.7

BGP: biogas plant
DC: dairy cows

9.1.3 Requirements in terms of land and labour

Before biogas is integrated into farm operations as a production branch, it will be necessary to take account not only of the high capital costs and tying up of land, but also of labour-management issues resulting from

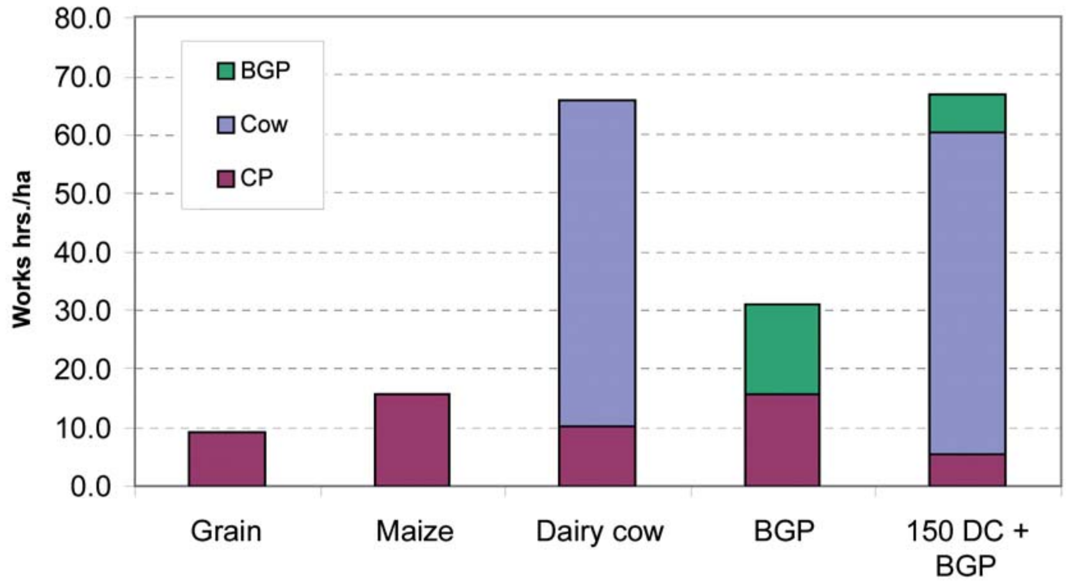

Figure 9.3: Required specific working times for various production branches with integrated biogas production (BGP: biogas plant, cow: animal husbandry with dairy cows (DC), CP: crop production)

changes to the cropping structure (e.g. growing maize instead of grain) and management of the biogas plant. Setting up a biogas plant involves a similar amount of capital being tied up per hectare as for milk production. The area of land required is determined by the size of the biogas plant plus the area needed for livestock rearing (see Table 9.1 and Table 9.2). For the purposes of calculation, the land required both for feed concentrate and also for basal feed was included under dairy cow husbandry.

The required area of land is used to calculate the required working time and tying-up of labour at the various times in the crop production cycle for the supply of substrate. Also the operation of an agricultural biogas plant requires the commitment of working time depending on the type and quantity of substrates used, technology, buildings and the way this business or production branch is integrated into an existing or future enterprise.

Example: Based on working time per unit of land area, a 150 kW biogas plant requires only about 50% of the hours worked compared with dairy cow husbandry on an equivalent area of land (cf. Figure 9.3). About 60% of the working time required for a biogas plant results from growing the substrates and about 40% from operation of the biogas plant. Where biogas production is combined with animal husbandry, there are significant synergistic effects in terms of profitability, emission reductions and often also labour management. It is important for the size of the biogas plant and therefore also the required working time to be matched to operational conditions on the farm.

In the conditions commonly found in eastern Germany, where the structure of agriculture is on a large scale, it has often proved a good idea if, for example, the person in charge of feed for the dairy unit, with his or her expertise in biological processes, is also made responsible for supervision of the biogas plant.

The working time required for operation of a biogas plant can be largely assigned to the following key process segments:

- production, harvesting and storage or procurement of raw materials (substrates);
- operation of the plant, including processing and loading of substrates;
- supervision of the plant, including process monitoring, maintenance, repair, rectification of faults/damage and administrative tasks;
- spreading digestate on the fields.

All of these process segments are essential for operation. However, depending on the mode of operation and substrate, they can require widely differing amounts of work. To avoid unpleasant surprises, working time planning must always be included in deliberations at the preplanning stage. There are, after all, tried-and-tested alternative solutions available.

For example, work relating to crop production, such as harvesting, transport and field spreading of digestate, can be shared between farms. Also in relation to plant operation, maintenance and monitoring (remote monitoring) can be carried out by specialist personnel in return for payment. Careful planning for each individual farm is the only way of identifying the appropriate, economically viable solution.

9.1.3.1 Production, harvesting and storage of raw materials

Where production takes place on the farm's own land, for example by growing maize for silage-making, by harvesting cereal plants for whole-crop silage or by harvesting grassland, there is a considerable volume of planning data available from conventional production techniques. As a rule, such data will also be applicable, without major adaptation, to the production of raw materials. The calculations in the following are therefore based on the well-known calculation documentation from the KTBL data collection on farm planning [9-1].

Required working time for producing substrates for model plant III

To illustrate and calculate the impacts on labour management, model plant III serves as an example (see also Chapter 8). This model plant processes manure from cattle farming, with a stock of around 150 livestock units (dairy cows). The energy crops used in this case are 5,750 t of maize silage and 200 t of cereal grain. If yields for maize silage are estimated at 44 t/ha (50 t/ha silage maize less 12% silage losses) and those for cereal grain at 8 t/ha, this is equivalent to a cultivated area of roughly 156 ha for energy crops (131 ha for maize and 25 ha for grain).

It is not crucially important whether the land is owned or rented, or whether it is made available through a land swap or by cooperation within an association. The land is no longer available for the supply of basal feed. Whether balanced crop rotation is generally maintained is something that needs to be examined.

Model plant III is assumed to have good production conditions, with an average field size of 5 ha and a distance from farm to field of 2 km. The farm has little silage maize harvesting equipment of its own, because, in small-scale agriculture, it is better for demanding work involving high capital expenditure to be outsourced. It is assumed that the farm itself performs all the work associated with the grain harvest.

Given these assumptions, the total required working time can be estimated at roughly 800 worker-hours per year (not including the spreading of digestate).

Tables 9.3 and 9.4 below show examples of the expected required working times. The figures are taken from the KTBL database, which offers a variety of planning variants.

During the period of silage maize harvesting, in September and early October, about 800 worker-hours are required (depending on the equipment used) for removal of the crop from the field to the silo and for storage in the silo with a wheel loader.

It is striking that each tonne of produced substrate is 'debited' with about 0.27 worker-hours, including the spreading of digestate, i.e. with labour costs of €4.00 based on a wage of €15.00 per hour.

Table 9.3: Sequence of labour operations and required working times for the maize silage process

Work process: maize silage	Worker-hours/ha
Cultivation	4.9
Harvesting and transport outsourced	0
Total worker-hours for maize	**4.9**

Table 9.4: Sequence of labour operations and required working times for the grain production process

Work process: grain	Worker-hours/ha
Cultivation	5.07
Harvesting and transport	1.1
Total worker-hours for grain	**6.17**

The production of silage and grain results in a required working time in the individual seasons of the year that would equally need to be allowed for if the use were a different one, such as selling or feeding. A common feature of these production processes is that a stored product is put to identical use over a long period of time, usually even throughout the year. This can be beneficial for management of the process as a whole. Whatever the case, the working time required for supplying the substrates to the biogas plant is relatively uniform with little variation.

The required working time becomes much less easy to plan and predict if residual materials arise

Table 9.5: Required working time for supervision of biogas plants

Work operation	Unit	Average	Min.	Max.
Routine inspection[a]	h/week	4.4	0.0	20.0
Data collection[a]	h/week	2.7	0.0	9.9
Maintenance[a]	h/week	3.2	0.0	14.0
Fault rectification[b]	h/week	2.7	---	---
Total	**h/week**	**13.0**		

a. based on [9-2], modified
b. [9-3]

during the growing seasons and only for certain periods of time and need to be processed. Relevant examples are the use of freshly cut foliage or of vegetable waste that arises at certain times only. In terms of labour management and process control, it will always be of advantage, wherever seasonally arising substrates are used, if there is an available store of 'reserve substrates' to fall back on in order to prevent temporary gaps in supply.

Another factor that should not be ignored is the negative effect on the digestion process from excessive variation in substrate composition if most of the substrates used are seasonal.

This issue assumes even greater significance if the substrates do not originate from the same farm. In this case, the required working time for substrate sourcing should not be underestimated. However, virtually no knowledge is available on the actual amount of working time required. It is ultimately down to the commercial skills of the operator to guarantee a lasting and, where possible, continuous supply. Where the substrates are picked up by the biogas plant operator, the time required for such work will plainly have an effect on the organisation of work at the farm and also on the associated costs.

Transport within or between farms is unavoidable, regardless of whether a biogas plant is operated individually or, especially, collectively. Not only does the additionally required working time need to be included in the plans, but the associated costs may also become critically important. The use of slurry or solid manure from animal husbandry or of wastes from product processing (grain, beet, vegetables, fruit) is likely to enter into consideration particularly frequently. It is always crucial to weigh the 'product value' for power generation against the 'price', including transport.

Whether or not a potential substrate is economically worth transporting should be clarified in advance at the stage when cooperation agreements or supply contracts are being signed. This is particularly true when deciding on the location of the plant.

9.1.3.2 Required working time for supervision of a biogas plant

The second biogas measuring programme (Biogas-Messprogramm II) included a comprehensive data survey on required working times based on operational logs from 61 biogas plants in Germany over a period of two years [9-2]. The collected data were systematised and evaluated to produce the average values listed in Table 9.5.

The average value given in this table for rectification of technical faults/biological process failures in biogas plants results from evaluation of data from 31 biogas plants as part of a project to analyse weak points in biogas plants [9-3].

Evaluation of these and other data reveals that an increase in nominal plant capacity is accompanied by a rise in total required working time in worker-hours per week (cf. Figures 9.4 and 9.5). Also, the results of the second biogas measuring programme demonstrate a close relationship between herd size, substrate input in t/week and required working time.

Unfortunately, the figures for required working time do not allow any further reliable conclusions to be drawn as to specific key areas of work.

It should be noted that, whereas the study [9-4] did not take account of required working time for fault rectification, the study [9-5] did include such time when calculating the working time required for plant supervision.

Furthermore, as the above-mentioned sources do not give a precise breakdown of the types of work involved in plant supervision, the data are not compar-

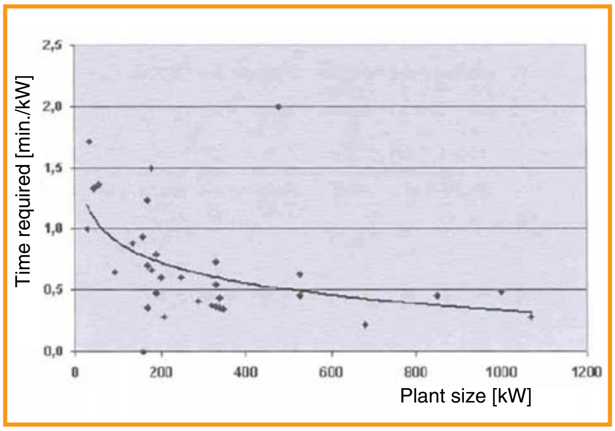

Figure 9.4: Required working time for plant supervision [9-4]

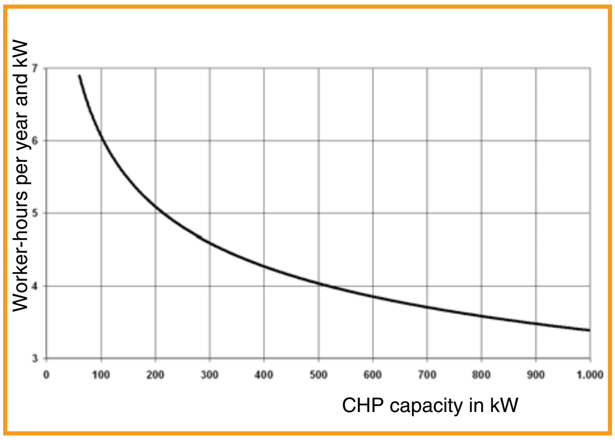

Figure 9.5: Required working time for plant supervision and maintenance [9-5]

able; nor is it possible to decide precisely which work is attributable to the biogas plant and which is not.

The profitability analyses of the model plants are based on the results from [9-5].

Required working time for supervision of model plant III

According to the data from [9-5] as outlined above, supervision of a biogas plant, including fault rectification, takes 4.5 hours per day. This means that, even for this size of plant (350 $kW_{el.}$), it is necessary to make allowance for half of one worker's time for supervision of the biogas plant, including routine activities, data collection, monitoring, maintenance and fault rectification.

9.1.3.3 Required working time for substrate processing and loading into the digester

The work involved in substrate allocation, removal from storage and, in some cases, processing is identical with other types of agricultural work. This makes it possible to use data from such other types of agricultural work to establish guide values that can be expected to be sufficiently reliable. On an overall view, it must be pointed out that the labour costs for operation of a biogas plant account for less than 10% of total costs and are therefore not crucially significant for profitability. Nevertheless, where labour is in short supply it may be necessary to resort to third-party services, which have to be taken into account in the profitability analysis. It should be noted that more reliable guide values for required working times will be needed in future to allow more accurate planning.

The required working time for substrate processing and loading into the digester is highly dependent on the type of substrate.

Table 9.6: Required loading times using various types of loading equipment (based on [9-6], [9-7], [9-8])

Material for loading	Loading times in [min/t]		
	Front loader, tractor	Wheel loader	Telescopic loader
Maize silage (horizontal silo)	4.28...8.06	6.02	3.83
Grass silage (horizontal silo)	4.19...6.20	4.63	3.89
Maize silage (horizontal silo), gravel track, sloping	5.11	2.44	-
Grass silage (horizontal silo), gravel track, sloping	5.11	3.66	-
Solid manure (manure store)	2.58	2.03	-
Large bales (rectangular)	1.25	-	1.34
Grain (loose)	2.61[a]	-	1.50[a]

a. Corrected provisional values

Table 9.7: Calculation of required working time/year for substrate processing and loading, including setting-up times, for model plant III

Substrate	Unit	Maize silage	Grain
Substrate quantity	t/year	5,750	200
x loading time	min/t	3.83	1.50
Required working time for loading	worker-hours/year	368	5
+ setting-up time	min/working day	5	
x working days	working days/year	365	
Required working time for setting up	worker-hours/year	30	
Total required working time	**worker-hours/year**	**403**	

Liquid substrates, such as slurry, are normally stored temporarily in or near the animal shed, fed into a receiving tank and pumped from there into the digester by pump units that are switched at specific times or intervals (cf. Section 8.1 Description of model plants). The required working time is restricted to occasional checks and adjustments and should be covered by the above-mentioned guide values for maintenance work.

The situation is similar for liquid pomaces and pulps from wine, brandy or fruit juice production.

Liquid fats and oils are pumped from the delivery vehicles into tanks or separate pits. Also in this case, the required working time is generally limited to checks and adjustments.

Maize silage and grass silage of agricultural origin account for the majority of **solid substrates**. Other such substrates that enter into consideration are cereal grains and wastes arising from the cleaning and processing of grain. Another possibility is root and tuber crops (beet, onions, potatoes) as well as the residues from their processing.

The greatest proportion of required working time is taken up by loading substrate into the holding vessel. As a rule, mobile loading and conveying machinery is used for filling the various digester loading systems (via a receiving tank or loading hopper of an angled conveyor/hydraulic press-in device). The example below shows basic module times that can be used for planning purposes. As yet, no specific working time measurements have been carried out in biogas plants.

Table 9.6 presents a summary of loading times using various types of loading equipment.

The required working time for substrate allocation can be estimated by taking the guide values for loading times and multiplying them by the quantities of substrate processed each year; it is then necessary to add an allowance for the required setting-up time.

Particularly at a large biogas plant, the time needed to drive from the silo face to the biogas plant can significantly increase the required working time. Such an increase in required working time can be offset by a suitable choice of plant location and technology.

Required working time for substrate processing and substrate loading for model plant III

It is assumed that a telescopic loader is used for filling the loading equipment. An additional allowance of 15 minutes per day is included as setting-up time for machine refuelling, removal of the silo plastic sheet cover and replacement of the cover. Therefore, the required working times for substrate processing and loading add up to a total of 403 worker-hours per year (see Table 9.7).

9.1.3.4 Required working time for field spreading of digestate

In model plant III, of the roughly 8,950 t of substrate used per year (manure and energy crops), approximately 71% of volatile solids is converted into biogas. Conversion reduces the mass of digestate to the extent that only about 7,038 t of the original substrate mass needs to be spread on fields.

The calculations do not include any required working time for spreading the quantities of manure contained in the substrate, because the mass of manure loaded into the biogas plant would have incurred spreading costs even without anaerobic treatment. Given identical spreading conditions and technical equipment, the required working time can be estimated to be the same.

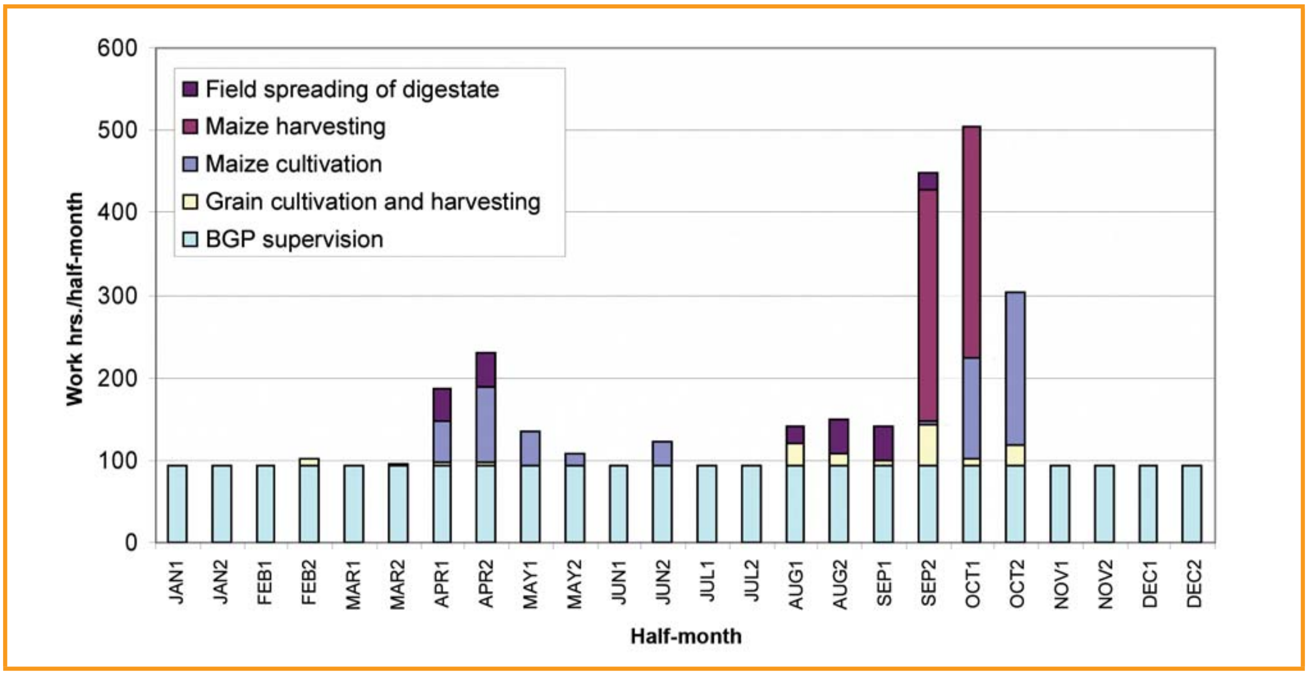

Figure 9.6: Chart of required working times for model plant III

Using a 12 m³ slurry tanker with trailing hose on five-hectare plots of land, at a distance from farm to field of 2 km and at an average spreading rate of 20 m³ of digestate per hectare, the required working time is 1.01 worker-hours per hectare or 3.03 worker-minutes per m³. The additional quantity of digestate to be spread, i.e. 4,038 t (7,038 t - 3,000 t manure), results, therefore, in a required working time of 204 worker-hours per year. A total of 355 worker-hours per year should be set aside for spreading digestate.

Required working time for model plant III
In summary, the annual required working time for **model plant III** can be calculated at roughly 3,126 worker-hours, on the assumption that time-consuming harvesting work will be contracted out.

At around 2,230 worker-hours, year-round supervision of the plant, including the loading of substrate, is characterised by a relatively uniform and regularly recurring workload. This work will require, say, one permanent full-time employee.

The required working time for growing 131 ha of silage maize comes to 641 worker-hours (including the appropriate share of time for spreading of digestate), with harvesting being outsourced to a third party. However, some 490 worker-hours are required for transporting, storing and compacting the harvested produce in a horizontal silo, work which the farm may be able to carry out itself.

9.1.4 Time as a factor in technology

The principal objective in the operation of a biogas plant is to make best possible use of the installed capacity for power generation, without the need for biogas to be released unused, for example via an emergency flare.

This calls, above all, for the engine in the combined heat and power unit to be operated at high load. A high rate of capacity utilisation will be achieved if the engine is run at full load, i.e. at close to maximum efficiency, for as many hours of the year as possible. The installed capacity of the engine must therefore be matched as closely as possible to the realistically expected biogas yield.

Preliminary plans very often assume an engine running time of 8,000 hours at 100% full load. Plans that include greater allowance for economic risks occasionally assume an annual running time of only 7,000 hours ('safety margin').

However, a running time of 7,000 hours per year means that, to be able to recover the energy from the biogas produced by the digestion process, the engine must have an at least 13% higher capacity than one that runs for 8,000 hours per year. The additional capital expenditure on this extra capacity (including for all other gas supply, storage and purification facilities) must be included in the calculations with €1,000/kW. It must also be borne in mind that the engine should not be subjected to excessive strain by daily alternating stop-start operation. For this reason, and in order to guarantee a constant supply of process heat (an engine can supply heat only if it is running), the work required from the engine in 7,000 hours of full-load operation per year can only be produced if the engine is run almost continuously at part load (90% of rated capacity). Part-load operation always signifies a loss of efficiency. Efficiency losses are almost always at the expense of the amount of electricity fed into the grid and hence at the expense of the operator's revenues. A detailed overview of economic losses, for example from a 5% reduction in efficiency, is given in Section 8.3 Sensitivity analysis.

From an economic standpoint, therefore, the aim must be to run the CHP unit at 8,000 full-load hours per year. Given this level of utilisation of the engine's capacity, however, it must be ensured that an adequate gas storage volume (> 7 h) is held available and that an efficient gas storage management system is in place. In normal operation, the gas storage tank should be no more than 50% full. This is for the following reasons:

- it must be able to accommodate the additional gas output arising during homogenisation;
- it must be able to cope with the increase in volume caused by exposure to the sun;
- it must be able to store gas in the event of malfunctions in the CHP unit or in the event of a grid-related shutdown.

9.2 References

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10 Quality and utilisation of digestate

10.1 Properties of digestate

10.1.1 Properties, nutrients and value-giving substances

The properties and constituents of digestate are determined essentially by the materials used for anaerobic digestion as well as by the digestion process itself. Agricultural biogas plants in Germany use mainly cattle and pig slurry, cattle and pig dung and poultry manure from poultry fattening. Less common is the use of farm fertiliser from laying hen farming, on account of the high concentrations of ammonium and residues from the supplementary feeding of calcium. Owing to the rules on remuneration laid down in the Renewable Energy Sources Act (EEG), only few plant operators continue to focus exclusively on the use of energy crops. Nevertheless, mention should be made of the long-known and valued effects of the digestion of farm fertiliser on the properties of digestate:

- reduced odour emissions through degradation of volatile organic compounds;
- extensive degradation of short-chain organic acids and consequent minimisation of the risk of leaf burn;
- improved rheological (flow) properties and consequent reduction of leaf fouling on fodder plants and simpler homogenisation;
- improved short-term nitrogen efficiency through increased concentration of rapid-action nitrogen;
- killing-off or inactivation of weed seeds and germs (human pathogens, zoopathogens and phytopathogens).

The fact that it is mainly the carbon fraction of the substrate that undergoes change through digestion means that the nutrients it contains are preserved in their entirety. They are, if anything, made more readily soluble by the anaerobic degradation process and therefore more easily absorbable [10-1].

Where mainly energy crops are used to produce biogas, the biological processes with similar substrates/feedstuffs are comparable with those that take place in the digestive tracts of livestock. This is therefore bound to lead to the production of a digestate with properties similar to those of a liquid farm fertiliser. This is confirmed by a study carried out by LTZ Augustenberg (Agricultural Technology Centre Augustenberg), which examined digestates from working farms in Baden-Württemberg with regard to quality and quantity of nutrients, value-giving substances and fertilising effect. Table 10.1 presents the parameters of the digestates [10-2]. The study dealt with digestates from the digestion of cattle manure and energy crops; pig manure and energy crops; mainly energy crops; and wastes (sometimes mixed with energy crops). To support the results, control samples of untreated manures were analysed. The key findings from the study are:

- the dry matter content of digestate (7% of FM on average) is around 2% lower than that of raw manure;
- the total nitrogen concentration in digestates with 4.6 to 4.8 kg/t FM is slightly higher than in cattle manure;
- the C:N ratio in digestates is approximately 5 or 6 and thus significantly lower than in raw manure (C:N 10);
- the degradation of organic matter causes organically bound nitrogen to be converted into inorganically bound nitrogen and therefore results in the ammonium fraction making up a higher proportion (approx. 60% to 70%) of total nitrogen in digestates;
- digestates mixed with pig-manure digestate and biowaste digestate tend to have higher concentrations of phosphorus and ammonium nitrogen, but lower concentrations of dry matter and potassium as well as lower concentrations of organic matter than digestates from cattle manure or energy crops or mixtures of the two;

Table 10.1: Comparison of parameters and value-giving properties of digestates and farm fertilisers [10-2]

Parameter	Unit/name	Raw manure	Digestate			
		Mainly cattle manure	Cattle manure and energy crops	Pig manure and energy crops	Energy crops	Waste (and energy crops)
Dry matter	% FM	9.1	7.3	5.6	7.0	6.1
Acidity	pH	7.3	8.3	8.3	8.3	8.3
Carbon to nitrogen ratio	C:N	10.8	6.8	5.1	6.4	5.2
Alkaline-acting substances	kg CaO/t FM	2.9	-	-	3.7	3.5
				kg/t FM		
Nitrogen	N_{total}	4.1	4.6	4.6	4.7	4.8
Ammonium-N	NH_4-N	1.8	2.6	3.1	2.7	2.9
Phosphorus	P_2O_5	1.9	2.5	3.5	1.8	1.8
Potassium	K_2O	4.1	5.3	4.2	5.0	3.9
Magnesium	MgO	1.02	0.91	0.82	0.84	0.7
Calcium	CaO	2.3	2.2	1.6	2.1	2.1
Sulphur	S	0.41	0.35	0.29	0.33	0.32
Organic matter	OM	74.3	53.3	41.4	51.0	42.0

FM: Fresh mass

- no significant differences are detectable with regard to magnesium, calcium or sulphur.

10.1.2 Contaminants

The concentrations of contaminants in digestates are essentially dependent on the substrates used. Table 10.2 shows guide values for concentrations of heavy metals in digestates in comparison with farm fertilisers. The absolute quantities of heavy metals do not change during the biogas process. The concentrations of heavy metals after digestion are increased by reference to the dry matter and the degradation of organic matter. The limit values for heavy metals laid down in BioAbfV (Biowaste Ordinance) [10-23] are exploited to only max. 17% for lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni) and mercury (Hg), and to 70% and 80% for copper (Cu) and zinc (Zn). Overall, the concentrations of heavy metals are similar to those in cattle manure. Pig manure has significantly higher concentrations of Pb, Cd, Cu and Zn. Although Cu and Zn are classed as heavy metals, they are also essential micronutrients for livestock and crops as well as for the microbiological processes in a biogas plant. They are added both to animal feed and also to energy crop biogas plants. Therefore, no limit values were laid down for Cu and Zn in the Fertiliser Ordinance (DüMV). At the given concentrations, the utilisation of digestate cannot be expected to give rise to any contamination of soils or watercourses.

10.1.3 Hygienic properties

Liquid manure and other organic wastes can contain a number of pathogens capable of causing infection in both humans and animals (Table 10.3).

Mass screenings continue to come up with positive salmonella findings (Table 10.4). Although the percentage of positive salmonella findings is below 5%, clinically healthy livestock are also affected. To break the cycle of infection, therefore, it is a good idea also to hygienise digestates that have been produced exclusively from farm fertilisers of animal origin, particularly if they are brought onto the market. In many cases, however, it is legally permissible not to hygienise the farm fertiliser part of a biogas plant. While other co-substrates of animal origin as well as wastes from biowaste bins are subject to strict rules on hygienisation, these rules are not always complied with, as is demonstrated by the finding from the biogas plant using biowaste as substrate.

With regard to phytohygiene, hygienisation measures must be applied in particular to prevent the spread of quarantine pests. Of particular importance in this respect are potato and beet diseases (*Clavibacter michiganensis*, *Synchytrium endobioticum*, *Rhizoctonia*

Table 10.2: Comparison of concentrations of heavy metals in digestates and farm fertilisers

	Digestate mg/kg DM	Exploitation of declaration values acc. to DüMV %	Exploitation of limit values acc. to DüMV %	Exploitation of limit values acc. to Bio-AbfV %	Cattle manure mg/kg DM	Pig manure mg/kg DM
Pb	2.9	2.9	1.9	< 5	3.2	4.8
Cd	0.26	26	17.3	17	0.3	0.5
Cr	9.0	3	-[a]	9	5.3	6.9
Ni	7.5	18.8	9.4	15	6.1	8.1
Cu	69	14 [c] (35)	-[b]	70	37	184
Zn	316	31[c] (158)	- [b]	80	161	647
Hg	0.03	6	3.0	< 5	-	-
Source	[10-2]	[10-19]	[10-19]	[10-23]	[10-3]	[10-3]

a. Limit value for Cr(VI) only
b. DüMV does not specify a limit value
c. Declaration value for farm fertiliser
DM: Dry matter

Table 10.3: Pathogens in liquid manure and organic wastes [10-4]

Bacteria	Viruses	Parasites
Salmonellae (CS, PS, PE)	Foot-and-mouth disease pathogens	Roundworms
Escherichia coli (CS)	Swine fever	Palisade worms
Anthrax bacteria (CS)	Swine vesicular disease	Trematodes
Brucellae (CS, PS)	Swine flu	Liver fluke
Leptospirae (CS, PS)	Transmissible gastroenteritis (TGE)	Lungworms
Mycobacteria (CS, PS, PE)	Rotavirus infections	Gastro-intestinal worms
Erysipelas bacteria (PS)	Teschen disease	
Clostridia (PE)	Aujeszky's disease	
Streptococci	Atypical bird flu	
Enterobacter	Bluetongue disease	
	Retro-, parvo-, echo-, enteroviruses	

CS: cattle slurry; PS: pig slurry; PE: poultry excrement

Table 10.4: Incidence of salmonellae in substrates and digestates of biogas plants

	Raw manure			Digestate	
	Cattle manure, pig manure, clinically healthy		Mainly cattle manure	Manures and energy crops	Biowaste and energy crops
Number of samples	280	132	51	190	18
of which salmonella positive	7	5	0	6	2
in %	2.5	3.8	0	3.2	11.1
Year of sampling	1989	1990		2005 to 2008	
Source	[10-5]	[10-5]	[10-2]	[10-2]	[10-2]

solani, *Polymyxa betae* and *Plasmodiophora brassicae*). For this reason, waste and wastewater from the food industry should always be hygienised before being used in a biogas plant [10-6].

The LTZ screening study examined almost 200 manures and digestates for the following fungal phytopathogens that are characteristic of maize and cereals: *Helminthosporium*, *Sclerotinia sclerotiorum*, *Phytium intermedium* and *Fusarium oxysporum*. However, a pathogen was detected in only one case [10-2].

10.2 Storage of digestate

Storage in a suitable tank is a prerequisite for utilisation of the nutrients and value-giving substances contained in digestate. As with untreated farm fertiliser, during the storage of digestate there are emissions of climate-relevant gases such as methane (CH_4) and nitrous oxide (N_2O) as well as emissions of ammonia (NH_3) and odorous substances.

10.2.1 Emissions of ammonia

The ammonium concentration, which is increased by the digestion process, as well as high pH values in digestate (cf. Tab. 10.1) promote the emission of ammonia during storage. Formation of a floating layer is usually possible only to a limited extent. In order to prevent ammonia losses from open digestate storage tanks, therefore, it is strongly advised to cover the digestate, for example with chopped straw, also because of the odorous emissions associated with ammonia (Tab. 10.5).

10.2.2 Climate-relevant emissions

In comparison with untreated manure, methane formation from digested manure is considerably reduced by the anaerobic process, because some of the organic matter contained in the substrate has already been metabolised in the digester, which means that there is significantly less easily degradable carbon in the storage tank. Therefore, the extent to which emissions of

Table 10.5: Coverings for digestate storage tanks for reducing emissions of ammonia[a] [10-7]

Covering materials	Capital costs (∅ 15 m) €/m²	Useful life Years	Annual costs €/m²	Reduction in emissions compared with uncovered tanks %	Remarks
Natural floating layer	-	-	-	20-70[b]	Low effectiveness if digestate is frequently spread on fields
Chopped straw	-	0.5	< 1	70-90	Low effectiveness if digestate is frequently spread on fields
Pellets	11	10	2.5	80-90	Material losses must be balanced out
Float	35	20	3.2	90-98[c]	Long useful life, new, little experience
Floating plastic sheet	38	10	5.3	80-90	Low maintenance, not suitable for very large tanks owing to high costs
Tent canvas	50	15	5.3	85-95	Low maintenance, no rainwater ingress
Trafficable concrete slab	85	30	6.2	85-95	Low maintenance, no rainwater ingress, up to approx. 12 m diameter

a. To date, few studies have been conducted into reducing emissions from real-world plants. The information given here is based on experience and investigations with pig manure.
b. Depending on the characteristics of the floating layer
c. Not suitable for viscous digestates
Assumptions: Interest rate: 6%; repairs: 1% (only for floating plastic sheet, tent canvas and concrete slab); pellets: 10% annual losses in case of pellets; cost of straw: €8/dt straw (baling, loading, transporting, chopping, spreading), required quantity: 6 kg/m²

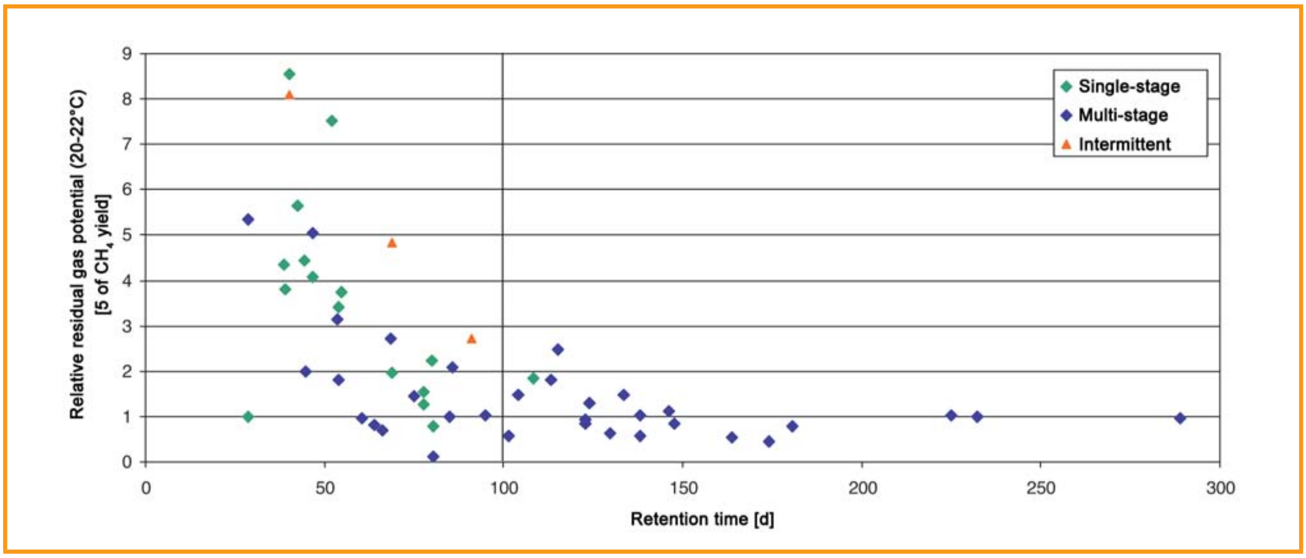

Figure 10.1: Correlation between relative residual gas potential at 20-22 °C and hydraulic retention time [10-8]

methane are reduced will depend decisively on the degree to which the organic matter has been degraded and consequently also on the retention time of the substrate in the digester. For example, it has been demonstrated in various studies that digestates with a short digestion phase, i.e. a short retention time in the digester, will emit more CH_4 than digestates with a longer retention time in the digester (Figure 10.1).

If the retention time is very short, there can be increased emissions of methane in comparison with untreated manure if substrate that has just been inoculated with methane-forming bacteria is removed from the digester after a short time and transferred to digestate storage [10-9]. Short-circuit streams should therefore be avoided.

To estimate the methane emissions from digestate, it is possible to use the results from batch digestion experiments with digestates at 20-22 °C [10-8], since this more or less corresponds to the temperature in a digestate storage tank under real-world conditions. On the other hand, the values for residual gas potential obtained under mesophilic conditions (37 °C) cannot be relied on with regard to actual emissions. Nevertheless, they can still give an indication of the efficiency of the digestion process, because they reflect the biomass potential still present in the digestate, i.e. the biomass potential that was not converted in the digester. Both parameters depend, however, on process control and also on the substrates used at the particular plant. Consequently, the values given in Table 10.6 should be regarded merely as a guide.

Multi-stage plants tend to exhibit a lower residual gas potential both at 20-22 °C and also at 37 °C (Table 10.6). This is due above all to the fact that a multi-stage plant has a higher retention time, which has the effect of reducing the residual gas potential (Figure 10.1).

Owing to the high greenhouse potential of CH_4 (1 g CH_4 is equivalent to 23 g CO_2), it is desirable to reduce or prevent CH_4 emissions from digestate storage tanks. Plants without gas-tight end storage should, in addition to multi-stage operation (digester cascade), meet at least one of the following requirements:

- average hydraulic retention time of the total substrate volume of at least **100 days** at a continuous digestion temperature throughout the year of at least 30 °C **or**
- digester organic loading rate **< 2.5 kg VS/m_N^3· d**.[1]

Calculation of the substrate volume must take account of all inputs into the digestion tank(s) (including, for example, water and/or recirculate). If the above-mentioned requirements are not met, methane emissions must be expected to exceed the average values given in Table 10.6. In such cases, it is advisable to retrofit the digestate storage tank(s) with a gas-tight seal[2] for at least the first 60 days of required digestate storage.

1. m_N^3 : Total usable digestion volume.
2. Digestate storage tank(s) must meet the following requirements: a) there must be no active temperature control and b) the tank must be connected to the gas-transporting system. Effective prevention of CH_4 emissions from the digestate is already achieved by covering for the first 60 days of required digestate storage, because, as is known from experience, methane formation under the conditions prevailing in a real-world plant will have been completed within that period.

Table 10.6: Residual gas potential of digestates from agricultural biogas plants, based on methane yield per tonne of substrate input; average values as well as minimum and maximum values from 64 operational plants sampled as part of biogas measuring programme II [10-8]

Process temperature		Residual gas potential [% of CH_4 yield]	
		Single-stage	Multi-stage
20–22 °C	Average	3.7	1.4
	Min–max	0.8-9.2	0.1-5.4
37 °C	Average	10.1	5.0
	Min–max	2.9-22.6	1.1-15.0

According to the 2009 Renewable Energy Sources Act (EEG), covering of digestate storage tanks is a prerequisite for receipt of the NawaRo (energy crop) bonus in cases where the plant is licensable under the Federal German Pollution Control Act. This includes all plants whose total combustion capacity exceeds 1 MW (equivalent to approximately 380 kW_{el}) or whose manure storage capacity exceeds 2,500 m^3. While this applies to all new plants, interpretation of the Act is still under discussion with regard to existing plants as, in many cases, retrofitting of digestate storage tanks is either not possible or possible only to a limited extent (see above).

Also in the case of new plants that are licensable under building law, it is worth considering installing a gas-tight cover not only from an environmental standpoint, but also on economic grounds. Ultimately, the unexploited biomass potential means lost revenue, especially in cases where the residual gas potential is high. The additionally obtained residual gas can be:

- converted into additional electric power (increased electric work), which would provide additional revenue from power generation;
- utilised while keeping the engine load unchanged – the saving of raw substrate on the input side will be equivalent to the additional gas (short-term option where the CHP unit is already working at full capacity; possibility of increased revenue from additional feed-in of electric power).

Especially for plants run on a high proportion of energy crops (e.g. > 50% of fresh mass input), it can be worthwhile retrofitting a gas-tight cover on the digestate storage tank, in which case, because of the smaller volume of digestate to be covered – and consequently lower capital costs – there is the expectation of corresponding economic benefits for even low residual gas yields (Table 10.7). In the case of plants run exclusively or predominantly on farm fertiliser, the volume of digestate to be covered rises in line with the size of the plant, with the consequence that the additional revenues from power feed-in may not be sufficient to offset the costs of a gas-tight cover. The 2009 amendment of EEG introduced a manure bonus for plants at which manure makes up over 30% of fresh mass input. This results in correspondingly increased additional revenues, the outcome being that the break-even point is reached at a significantly lower installed capacity than in the case of plants run on a low proportion of manure. However, a significantly reduced residual gas potential can generally be expected in comparison with plants run on energy crops.

Table 10.7: Break-even points[a] for retrofitting gas-tight covers on cylindrical digestate storage tanks: minimum installed electrical capacity required for break-even for various capital costs of retrofitting [10-10; modif.].[b]

Manure as % of substrate input	< 30% (= remuneration without manure bonus)		> 30% (= remuneration with manure bonus)	
Usable residual gas	3%	5%	3%	5%
Capital costs (number/diameter of tanks)	Minimum electrical capacity[b] [kW]			
€33,000 (e.g. 1/ < 25 m)	138	83	109	66
€53,000 (e.g. 1/ > 25 m)	234	133	181	105
€66,000 (e.g. 2/ < 25 m)	298	167	241	131
€106,000 (e.g. 2/ > 25 m)	497	287	426	231
€159,000 (e.g. 3/ > 25 m)	869	446	751	378

a. Determination of break-even point based on comparison of unit costs (annual costs per additional kilowatt-hour) and actual tariff per kilowatt-hour fed in.
b. Calculation basis: CHP unit 8,000 full-load hours, pro rata costs of CHP unit upgrade according to additional capacity from utilisation of residual gas, efficiency according to ASUE (2005) [10-13], remuneration according to KTBL online remuneration calculator (2009). Capital costs and annual costs of cover; calculation based on a useful life of 10 years, gas-tight cover for first 60 days of digestate storage (period within which methane formation from the digestate will normally have been completed under real-world conditions).

A Germany-wide study carried out in 2006 by KTBL (Association for Technology and Structures in Agriculture) revealed that only around one quarter of existing cylindrical tanks (95% of the digestate storage tanks included in the study) were provided with a gas-tight cover [10-11]. This is consistent with results from biogas measuring programme II (FNR 2009). However, not all digestate storage tanks are technically suitable for retrofitting with a gas-tight cover. The team of experts accompanying the study came to the conclusion that such retrofitting is possible without problem for only one quarter of existing open cylindrical tanks. A further quarter of tanks were assessed as retrofittable with difficulty on account of structural/design issues. Half of cylindrical tanks were considered unsuitable for retrofitting, as were ground basins (approx. 5% of the digestate storage tanks included in the study) [10-11].

In cases where a tank is of limited suitability for retrofitting, it must be expected that the costs will be significantly higher than those presented above. For single-stage plants, an alternative option is to set up an additional digester, since there is here the expectation of an increased residual methane potential and consequent additional revenues, particularly in the case of short retention times.

Nitrous oxide is produced during nitrification from ammonium or denitrification of nitrate. As rigorously anaerobically stored manure or digestate contains only ammonium and nitrification cannot take place, the potential formation of nitrous oxide is restricted to the floating layer and will depend on its type and aeration. This is demonstrated also in studies into emissions of nitrous oxide from manure and digestate, some of which have led to highly differing results with regard to the influence of digestion on emissions of nitrous oxide. Usually, N_2O emissions from manure storage tanks are negligibly small in comparison with emissions of CH_4 and NH_3 and are insignificant for the assessment of greenhouse gas emissions [10-11]. A gas-tight cover, however, will prevent even those emissions entirely.

10.3 Utilisation of digestate on agricultural land

A sufficient delivery of organic matter to soil fauna, as well as a supply of nutrients matched to the needs of crops and type of soil, are fundamental prerequisites for the sustainable utilisation of agricultural land.

The rise in the price of mineral fertilisers in recent years has made the transport and field spreading of digestates and farm fertilisers economically worthwhile, with the consequence that digestates, because of their nutrient value, are normally worth the cost of transport. Also, fertilisation strategies based on digestates and farm fertilisers are more beneficial in terms of their energy balance than strategies that are founded exclusively on mineral fertilisers [10-12].

10.3.1 Availability and nutrient effect of nitrogen

As confirmed by analysis values (cf. Table 10.1), digestion normally reduces the dry matter content of substrates. Also, the C:N ratio in the digestate narrows as a result of methane digestion according to the degree of digestion. This has a favourable effect in relation to fertilisation, because there is an increase in the amount of ammonium available to the crops. The C:N ratio narrows from around 10:1 to approx. 5 to 6:1 for liquid manure and from 15:1 to 7:1 for solid manure. Consequently, however, some of the mineralisable organic matter has already been degraded. This means that, of the organically bound nitrogen, only around 5% is available to the crops in the year of application (3% in the following years) [10-12].

The available nitrogen from the applied digestate in the year of application can be calculated using mineral fertiliser equivalents (MFE). In the year of application, the MFE is determined mainly by the availability of ammonium nitrogen. In the following years, only small additional quantities of nitrogen are supplied from the digestate. If ammonia losses are extensively avoided, the 'short-term MFE' is 40-60%. This can be deducted from the mineral fertiliser requirement. In the case of longer-term application of digestate (after 10-15 years), an MFE of 60-70% can be assumed [10-12], [10-7].

Generally, however, it can be expected that the effectiveness of the nitrogen from digestate will depend decisively on the method and timing of field spreading, weather, type of soil and type of crop.

The higher pH value of digestate in comparison with raw manure has only an insignificant effect on ammonia losses, because the pH likewise reaches a value of 8 to 8.5 soon after raw manure has been spread. There is, therefore, no significant difference in terms of ammonia emissions [10-15].

Table 10.8: Cumulative ammonia losses after field spreading of farm fertiliser, without working into soil, at different temperatures, within 48 hours [10-7, modified]

Farmyard fertiliser	Ammonia losses in % of applied ammonium-N[a]			
	5 °C	10 °C	15 °C	25 °C, on straw
Cattle manure, viscous digestate[b]	30	40	50	90
Pig manure, thin digestate[b]	10	20	25	70
Liquid manure			20	
Deep-litter stall manure and solid manure			90	
Dry poultry excrement			90	

a. Emission of residual NH_4-N after storage.
b. Digestate assessed as cattle/pig manure since no field studies available.

10.3.2 Measures to reduce ammonia losses after field spreading of digestates

10.3.2.1 Emissions of ammonia

Table 10.8 presents the losses of ammonia after field spreading of farm fertilisers at different temperatures. It is apparent that ammonia losses increase with rising temperature. Particularly high losses can be expected when digestate is applied to crops or crop residues at high temperatures. The lowest losses can be expected when thin digestate, which is able to seep quickly into the soil, is applied at low temperatures. Simply choosing the best time to spread, therefore, can contribute significantly to reducing the losses of ammonia.

10.3.2.2 Field spreading techniques

The spreading of digestate on agricultural land as a fertiliser is performed using the same techniques as those applied in the utilisation of liquid farm fertilisers. Field spreading is carried out by liquid manure tanker, usually with emission-reducing application equipment (e.g. trailing hose applicator), which allows growing crops to be fertilised at times of maximum nutrient demand.

The purpose of spreading digestate on agricultural land must be to apply the nutrients contained in the digestate for selective fertilisation with similar accuracy to fertilisation with mineral fertilisers, in order to maximise the supply of nutrients to the crop roots and to minimise the losses of nutrients.

The following techniques are used for field spreading of digestate:

Tanker

A distinction is made between two common types:
- compressor tanker
- pump tanker

The techniques used for low-loss and precise spreading of digestate are explained in the following.

Trailing hose applicator

Trailing hose applicators have a working width of between 6 and 24 m; applicators with a working width of 36 m have recently become available. The individual discharge hoses are normally spaced apart at 20 to 40 cm intervals. The digestate is applied to the surface of the soil in approximately 5 to 10 cm wide strips.

Figure 10.2: Trailing hose applicator

Trailing shoe applicator

Trailing shoe applicators have a working width of between 3 and 12, sometimes 18 m; the individual discharge hoses are normally spaced apart at 20 to 30 cm intervals. The ends of the discharge hoses are provided with special spreading devices usually in the form of shoe-like reinforcements or skids, at the ends of which the digestate is applied.

During spreading in the field, the applicator is dragged through the crops (if any). It is inherent in the design of this applicator that the crops will be pushed slightly aside during spreading. The digestate is applied to the uppermost region of the soil (0 to 3 cm), with the result that contamination of the crops is largely prevented.

Cutting applicator

A typical disc applicator has a working width of between 6 and 9 m; the individual discharge hoses are normally spaced apart at 20 to 30 cm intervals. The manure is applied by means of a shoe-like reinforcement with a cutting disc (or steel blade) that cuts

Table 10.9: Reduction of ammonia losses after field spreading of liquid digestates[a] [10-7, modified]

Reduction techniques/ measures	Areas of use	Emission reduction [%] Digestate		Limitations
		Viscous	Thin	
Trailing hose technique	Arable land: Uncropped Crop height > 30 cm Grassland: Crop height up to 10 cm Crop height up to > 30 cm	 8 30 10 30	 30 50 30 50	Slope of terrain not excessive, size and shape of land, viscous digestate, interval between tramlines, crop height
Trailing shoe technique	Arable land Grassland	30 40	60 60	As above, not on highly stony soils
Cutting technique	Grassland	60	80	As above, not on stony, overly dry or compacted soils, high tractive power required
Manure injector technique	Arable land	> 80	> 80	As above, not on highly stony soils, very high tractive power required, limited usability on cropped arable land (limited to row crops)
Direct application (within 1 hour)	Arable land	90	90	With light implement (harrow) after primary tillage, with injector/plough after harvest

a. To date, few studies have been conducted into reducing the emissions from digestates; the information given here is derived from studies of cattle and pig manure.

Figure 10.3: Trailing shoe applicator

Figure 10.4: Cutting applicator

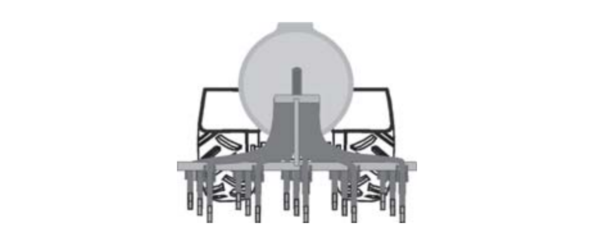

Figure 10.5: Manure injector

open the soil and at the end of which the digestate is applied to the thus exposed soil.

Direct application by manure injector

A manure injector has a working width of between 3 and 6 m; the individual discharge hoses are normally spaced apart at 20 to 40 cm intervals. The soil is worked by a tine, at the end of which the digestate is injected into the stream of earth while the soil is being worked. There are also disc harrows, which work the soil with concave discs, with the fertiliser being similarly injected into the stream of earth.

Table 10.9 lists the techniques available for application of liquid farm fertilisers and digestates. A wide range of different techniques can be used for field spreading, depending on the type of crop, stage of development and local conditions. Technical and local limitations in connection with field spreading mean that some of the ammonium will always escape into the atmosphere in the form of ammonia.

10.4 Treatment of digestates

The number and size of biogas plants in Germany are both rising sharply. There is also an intensification of livestock farming, including in regions already with a high cattle density. The result is a regionally high arising of farm fertiliser, with the consequence that there

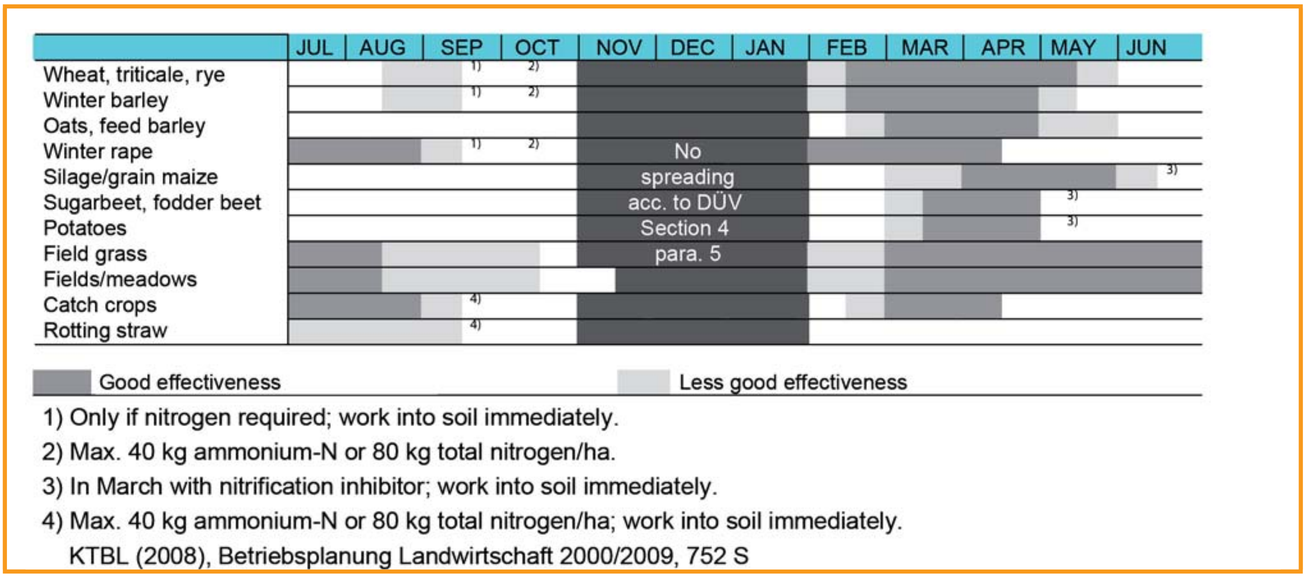

Figure 10.6: Field spreading periods for digestates

is frequently no point in using digestates a fertilisers. Such fertilisers not only have a high nutrient potential, but they can also overload the natural metabolic cycles unless correctly used. To effectively exploit this nutrient potential, it may be necessary and useful to increase the concentration of nutrients in order to obtain a fertiliser that is economically worth transporting and which can be used in regions without a surplus of nutrients.

The following describes the current status of technologies and processes for separation of nutrients from digestates. The degree of possible nutrient concentration as well as the cost and functionality of the processes are described and the processes evaluated. A comparison of the processes with current costs of digestate utilisation serves to assess the real-world usability of the processes.

10.4.1 Treatment techniques

The simplest way to use digestate is to spread it as fertiliser on agricultural land without prior treatment. In more and more regions, such a form of nearby use is either not possible or possible only to a limited extent. High rents for suitable land or long transport distances and associated high transport costs can make it difficult for digestates to be put to economically worthwhile use. Various processes are used (or are under development) to make digestates more economically worth transporting. Such processes may be of a physical, chemical or biological nature (Figure 10.7).

The following is confined to physical processes.

10.4.1.1 Utilisation of digestate without treatment (storage of untreated digestate and field spreading)

In the interests of nutrient recycling, it is desirable for digestates to be spread on the same land that was used to cultivate the energy crops used for digestion. As such land will normally be in the immediate vicinity of the biogas plant, the required transport distances are short and both transport and field spreading can be carried out at low cost using the same vehicle without the need for transloading (single-phase). For transport distances of around 5 km or more, transport and field spreading are carried out by separate vehicles. It is generally the case that, as the transport distance increases, the costs of both processes rise significantly, because the nutrient content of the digestate with reference to its transport mass is relatively low. The goal of digestate treatment, therefore, is to reduce the inert water content and to selectively increase the concentration of nutrient fractions.

10.4.1.2 Separation of solids

The separation of solids is fundamental to digestate treatment. It has the advantages of reducing the storage volume of liquid digestates as well as of lessening the incidence of sinking and floating layers during storage. Above all, however, the nutrients are fractionated, because, whereas soluble, mineral nitrogen remains mainly in the liquid phase, most of the organically bound nitrogen and phosphorus is separated with the solid phase. The separated, low-DM liquid

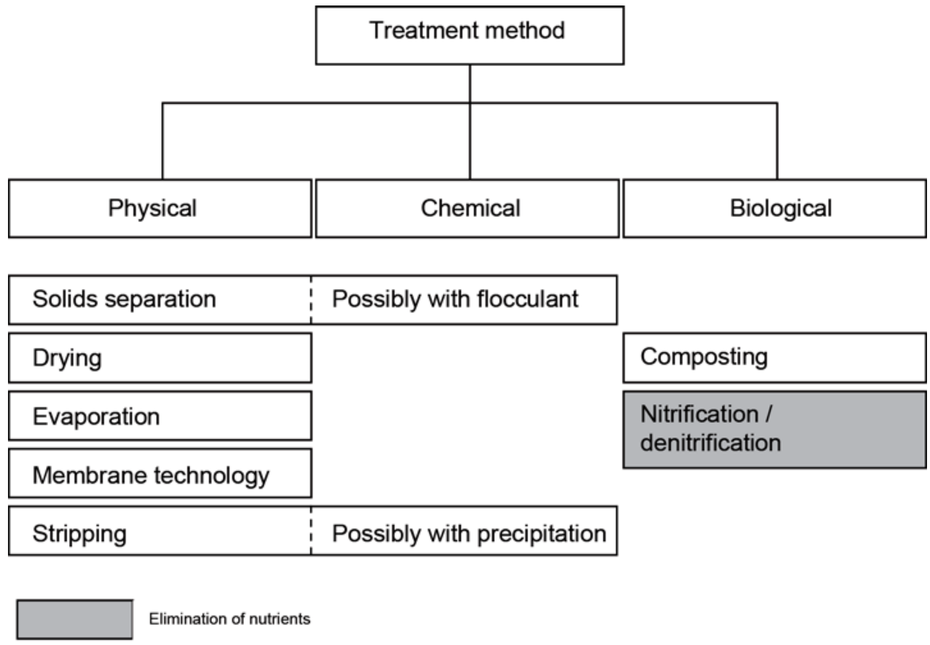

Figure 10.7: Classification of treatment processes by type

phase can be spread on fields or further treated, while the separated solids can be composted or dried. Depending on the required degree of separation, use is made predominantly of screw press separators, screen drum presses, screen belt presses and decanters.

The separation performance of all the processes is highly dependent on the properties of the digestate and on the adjustment of the separator. The higher the DM content of the digestate, the greater is the achievable volume reduction and separation of phosphorus and organic nitrogen with the solid phase. Screw press separators can attain dry matter concentrations of 30% in the solid phase. Although this is not normally possible with a decanter, this is the only technique for achieving dry matter concentrations below 3% in the liquid phase, which is a prerequisite for some further liquid phase treatment processes. Decanters, however, require the composition of the input material to be constant. Also, compared with separators, they are subject to higher wear and energy consumption.

Flocculants are sometimes used to improve the separation performance, in which connection it is necessary to take account of issues connected with German fertiliser legislation.

10.4.1.3 Further treatment of the solid phase

Direct field spreading of the separated solid phase is possible. As, however, this can lead to nitrogen immobilisation, odour development or dispersion of weed seeds, the separated solids are usually subjected to further treatment.

Composting

Composting is a form of aerobic treatment of organic wastes, the objectives being to stabilise the organic components, to kill off pathogenic germs and weed seeds and to eliminate odour-intensive compounds. Oxygen must be supplied in sufficient quantity to the digestate that is being composted. Since digestate rather lacks structure as a material, successful composting requires the addition of structural material (such as bark mulch) or frequent re-piling of the material.

Owing to anaerobic degradation of carbon in the biogas plant, there is reduced spontaneous heating during composting in comparison with untreated organic material. The temperatures reached during composting are only up to 55 °C and not the 75 °C that would be required for successful hygienisation.

Similarly to conventional compost, the resulting compost can be used directly as a soil conditioner [10-25].

Drying

Some drying processes already established in other areas can be used for this purpose. These include drum dryers, belt dryers and feed-and-turn dryers. In most dryer systems, the heat is transmitted by hot air flowing over and through the material to be dried. In a biogas plant, waste heat can be used for this purpose unless there are other uses for it.

During drying, most of the ammonium contained in the solid phase is passed to the waste air of the dryer in the form of ammonia. For this reason, waste air treatment may be required in order to prevent emissions of ammonia. Likewise, there may be emissions of odorants, which, if possible, should be removed from the waste air stream in a combined waste air cleaning process.

Dry matter concentrations of at least 80% in the solid phase can be achieved by drying. This makes the digestate suitable for storage and transport.

10.4.1.4 Further treatment of the liquid phase

The lower DM concentrations in the separated liquid phase make for easier storage and field spreading in comparison with untreated digestate. Frequently, however, additional volume reduction and/or nutrient enrichment in the liquid phase is desirable. This can be accomplished by the following processes.

Membrane technology

The treatment of organically heavily contaminated water using membrane techniques is already widespread in the area of wastewater treatment. Consequently, it has been possible for this full-treatment technology to be adapted relatively well to digestates and for it to be used at some biogas plants. Unlike most other digestate treatment processes, this process requires no heat. This makes membrane technology suitable also for plants that are connected to a micro gas grid or gas processing system and therefore have no surplus heat.

Membrane technology consists of a combination of filtration processes with decreasing pore size, followed by a reverse osmosis stage, which results in a dischargeable permeate and a heavily nutrient-enriched concentrate. The concentrate is rich in ammonium and potassium, while the phosphorus is trapped above all in the ultrafiltration stage and is present in the retentate. The permeate from reverse osmosis is extensively nutrient-free and of a quality suitable for direct discharge into a watercourse. The calculations assume that the two nutrient-rich liquid phases will be mixed for field spreading.

To prevent premature plugging of the membranes, the DM concentration in the liquid phase should not exceed a value of 3%. In the majority of cases, this requires solid/liquid separation in a decanter.

Evaporation

Evaporation of digestates is of interest for biogas plants with high surplus heat, because around 300 kWh_{th}/m^3 of evaporated water is required. This process is suitable only to a limited extent for plants that are run on a high manure concentration and which therefore have a high digestate volume in relation to the energy produced. For the model plant calculated here, with a content of 50% by mass of manure in the substrate input, only 70% of the required heat can be supplied by the biogas plant. Only a small amount of previous operational experience is available in relation to digestate evaporation plants.

A multi-stage process is usually applied. The material is first heated, with the temperature then being gradually increased under vacuum to boiling point. To prevent ammonia losses, the pH value in the liquid phase is lowered by the addition of acid. Technical problems during operation can arise through plugging and corrosion of the heat exchangers. A vacuum evaporation plant reduces the digestate volume by around 70%. Heating of the digestate to 80-90 °C during evaporation allows hygienisation to be included in the process.

In comparison with the input material, evaporation can achieve an up to fourfold increase in the solids concentration, which results in a corresponding reduction in storage and transport costs. However, direct discharge of the treated condensate is not possible, because the statutory limits cannot be met.

Stripping

Stripping is a process for removing substances from liquids in which gases (air, water vapour, flue gas, etc.) are transported through the liquid and the substances are converted to the gaseous phase. Ammonium is converted to ammonia. This process can be assisted by increased temperature and pH value, as is employed, for example, in steam stripping, because the required gas flow rate is reduced with increasing temperature. In a downstream desorption stage, the ammonia in the gaseous phase is converted into a recyclable/disposable product. Desorption of NH_3 from the gas stream can be accomplished by condensation, acid scrubbing or by reaction with an aqueous gypsum solution. The end products of desorption are usually ammonium sulphate and ammoniacal liquor.

As with evaporation, compliance with the statutory limits for discharge of the treated water cannot currently be guaranteed.

10.4.2 Utilisation of treated digestates

In terms of their properties, the **solids** from the separation process are comparable with fresh compost and can, like fresh compost, be used as fertiliser and to increase the concentration of organic matter in soils. The German Federal Compost Quality Association (BGK) has developed quality criteria for solid digestates and awards a seal of quality. Fresh compost, however, is used mainly in agriculture, as there can be an odour nuisance in connection with its storage and spreading on fields. A marketable product first requires stabilisation of the digestate, for example by composting. This, however, is uneconomic at approx. €40/t of solid. An alternative is to dry the solids as described above. This results in a storable and transportable product that can be used for targeted application of P and K (cf. Table 10.10) in soils with a high nitrogen loading.

Another option is to incinerate the dried solids. However, digestate is not approved as a main fuel under the Federal German Pollution Control Act (BImSchV) if manure or excrement is co-digested. This would require a special approval subject to an extensive set of conditions. For digestates of exclusively vegetable origin, the need for regulation is unclear.

In some biogas plants, the **liquid phase from separation** is sometimes used as recirculate. The reduced DM content also allows more precise field spreading with lower NH_3 losses. The lower phosphorus concentration compared with untreated digestates means that, in regions with intensive livestock farming, larger volumes can be utilised at nearby locations, where field spreading is normally limited by the phosphorus concentration in the soil. Problems of regional nitrogen surplus can usually be addressed only by further treatment of the liquid phase, since separation alone does not result in a reduction of the transport volumes.

The **nutrient-containing treatment products of the liquid phase** are often of only limited marketability. Although the nutrient concentrations are higher than those of digestates (Table 10.10), which makes them more economically worth transporting, they are usually significantly lower than the nutrient concentrations in mineral fertilisers. This can sometimes pose an obstacle to utilisation, because no suitable field spreading technology is available. Field spreading by trailing hose applicator, as employed for field spreading of manure and digestate, requires sufficiently high application volumes to allow uniform distribution of the nutrients in the soil. Mineral liquid fertilisers, such as ammonium-urea solution, with a nitrogen concentration of 28% are frequently applied using pesticide sprayers, which, however, usually have a limited application capacity. Application volumes significantly above 1 m^3/ha are difficult to achieve using standard technology.

The ammonium sulphate solution from stripping comes closest to meeting the standards required of a marketable treatment product. It has a nitrogen concentration of almost 10% and, as a product of exhaust air cleaning and by-product of the chemical industry, is already marketed in large volumes as an agricultural fertiliser.

With regard to **nutrient-depleted or nutrient-free treatment products of the liquid phase**, the economic calculations did not assume any utilisation costs or revenues. Revenues are possible here if offtakers can be found for process water. This appears most likely in the case of membrane technology, which produces a directly dischargeable permeate from reverse osmosis. An option for all virtually nutrient-free products would be use in sprinkling or irrigation, while, for products of dischargeable quality, discharge into a watercourse would be a possible alternative. Where such options do not exist, connection to a water treatment plant with appropriate hydraulic and biological capacities is required. This results in additional costs, which must be taken into consideration.

10.4.3 Comparison of digestate treatment processes

The digestate treatment processes described above differ significantly in terms of their current dissemination and operational reliability (Table 10.11). Digestate separation processes are state of the art and already in common use. Partial treatment, however, does not normally reduce the volume for field spreading and the cost of field spreading of digestates is increased.

Processes for drying the solid phase are already established in other application areas and are adapted for the drying of digestates. Few technical problems are to be anticipated in this connection. However, the drying of digestates is an economically attractive proposition only in cases where, once dried, the digestate can be profitably utilised or there is no other utilisation option for the waste heat from the biogas plant.

Processes for treatment of the liquid phase are not yet state of the art and there is a substantial need for

Table 10.10: Nutrient concentrations of fractions, model calculations for treatment processes

Treatment process	Fraction	Mass concentration %	N_{org} kg/t	NH_4-N kg/t	P_2O_5 kg/t	K_2O kg/t
Untreated	Liquid		2.0	3.6	2.1	6.2
Separation	Solid	12	4.9	2.6	5.5	4.8
	Liquid	88	1.6	3.7	1.6	6.4
Belt dryer	Solid	5	13.3	0.7	14.9	12.9
	Liquid	88	1.6	3.7	1.6	6.4
	Waste air	7	-	-	-	-
Membrane	Solid	19	4.9	4.4	6.8	4.5
	Liquid	37	2.8	7.4	2.1	14.4
	Wastewater (treated)	44	Limit values met for direct discharge into watercourse			
Evaporation	Solid	19	4.9	4.4	6.8	4.5
	Liquid	31	3.4	8.9	2.5	17.3
	Process water	50	Not suitable for discharge into watercourse			
Stripping	Solid	27	6.8	3.5	7.5	21.7
	Liquid (ASS)	3	0.0	80.6	0.0	0.0
	Process water	70	Not suitable for discharge into watercourse			

ASS: ammonium sulphate solution

Table 10.11: Comparative evaluation of digestate treatment processes

	Separation	Drying	Membrane technology	Evaporation	Stripping
Operational reliability	++	+/o	+	o	o
Dissemination status	++	+	+	o	o
Cost	+	+/o	o/-	o	+/o
Product usability					
Solid phase	o	+/o	o	o	o
Liquid (nutrient-rich)	o	o	+	+	++
Liquid (nutrient-poor)			+	o	o

++ = very good, + = good, o = average, - = poor

development. Membrane technology is furthest advanced. Here, there are several suppliers on the market as well as a number of reference plants that are in largely reliable operation. Nevertheless, even in this case, there is still development potential for modifying the process in order to reduce wear and energy consumption. For example, improved methods for the separation of solids are already under development, the goal being to extend the useful life of membranes and to reduce energy consumption.

Processes for evaporation and stripping are not yet so advanced in terms of commercial-scale continuous operation. For this reason, an economic assessment as well as the expected product quality are still subject to a substantial degree of uncertainty and the technical risks are comparatively high.

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11 Project realisation

The realisation of a biogas project encompasses all stages of work from concept formulation, feasibility study and plant engineering through to commencement of plant operation. When realising a biogas project, project initiators (e.g. farmers) have the option of carrying out certain phases of the project themselves, depending on their personal commitment and available financial and personnel resources. The individual phases of concept formulation, feasibility study, capital expenditure planning, permitting procedure, plant construction and commissioning are presented in Figure 11.1.

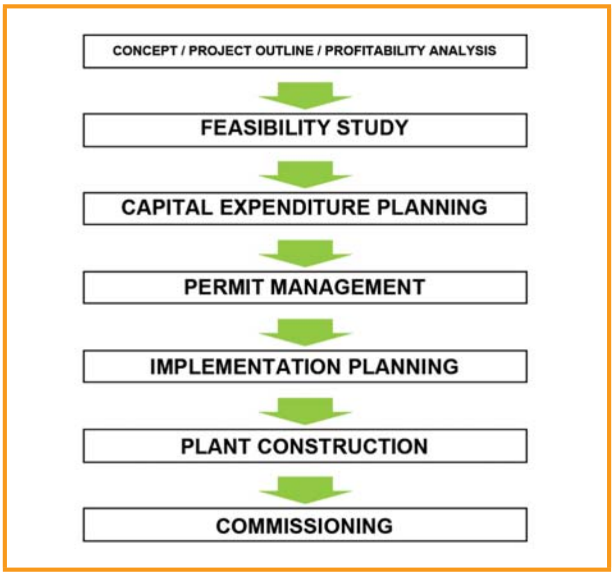

Figure 11.1: Steps in the realisation of a biogas production and utilisation project

To provide a comprehensive overview of the steps required for project realisation and to describe the key areas of work in detail, the following sections are presented mainly in the form of tabular checklists.

11.1 Concept formulation and project outline

Once the idea for a biogas project has been conceived, it is advisable for the project initiator to draw up a project outline as a basis for the project realisation process. This outline should serve also as an initial basis for project evaluation. The project outline is used to assess not only the site-specific technical feasibility of the project, but also how the project can be financed and whether it is eligible for government subsidy. The project outline is also useful for establishing initial key contacts with potential engineering firms. It is advisable to obtain some preliminary information from existing biogas plant operators about the planning procedure and operation of a biogas plant, especially if the intention is to use identical substrates.

When considering a biogas project, it is important to see the whole picture, including the availability of substrate, the actual biogas plant and the supply of energy to offtakers. The three key aspects presented in Figure 11.2 must be considered from the outset in the same degree of detail, the objective being to carry out a well-founded initial evaluation of the project concept.

To avoid any unnecessary additional problems in subsequent phases of planning, the project outline should be drawn up in the following steps and should be evaluated using the calculation methods made available in this Guide:

1. Calculation and examination of the available volume of substrate; determination of the biomass supply chain
2. Rough technical design of the plant
3. Review of the available area of land
4. Estimate of costs, eligibility for government subsidy and economic profitability
5. Review of energy offtake strategy

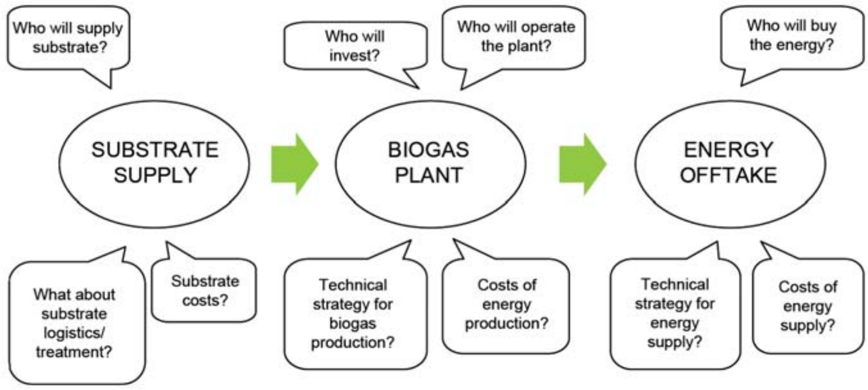

Figure 11.2: General approach to a biogas plant project

Step 1: Preparing the project outline	
Check out the long-term availability of substrates	Which **self-produced** substrates will be available on a long-term basis? Do I have medium-term/long-term plans to change my farm? How will this affect my biogas plant? (in terms of biology/materials, process, energy) Can I count long-term on substrates from **outside** my farm? Is the use of these substrates worthwhile in view of the statutory requirements? (question of proportionality)
Go and visit some existing biogas plants	Go and visit some existing plants as a way of acquiring experience and information. What structural options are available on the market? Where are there structural/process-related problems? How were those problems solved? What has been the experience of existing plant operators with various components and substrate combinations?
Work out how much time you yourself have available	Work out how much time will be required every day for routine inspection/maintenance work (cf. Section 9.1.3). Is this compatible with the situation on my farm? What working time model is possible for my family? (e.g. who will take over the farm after me) Will I need outside workers?
Check out how the heat from the plant can be utilised	Are there potential heat offtakers close to my farm? How much heat needs to be supplied every month?
Work out how much money you have at your disposal	Check your finances How do you expect your income situation to develop in future? Will your financial situation undergo any major changes in the near future?
Goals in Step 1:	- Initial assessment of the possibilities in terms of farm business organisation - Gathering of experience from real-world biogas plants - Acquisition of knowledge about what plants/components are available on the market

6. Assessment of whether the plant will be granted the required official permit and whether it will meet with local approval.

An initial evaluation of the project does not require definite decisions on the above-mentioned aspects (this will take place in the subsequent planning phase). Rather, the aim is to ensure that there are at least one or, if possible, several options for successful realisation of the project.

11.2 Feasibility study

Once the project initiator has made the decision, based on the project outline, to proceed to the next stage of the potential biogas project, it will be necessary to prepare a feasibility study. This will normally rely heavily on the project outline, the principal objective being to determine all the technical, economic and other initial data and parameters and to subject them to a thorough examination. In contrast to the project outline, which provides an initial qualitative evaluation of the planned project, the purpose of the feasibility study is to deliver a quantitative assessment of the envisaged project as well as possible options for its realisation.

The key criteria to be applied for a feasibility study on a biogas plant project are presented in Figure 11.3 and are examined in greater detail in the below sections.

A feasibility study provides a decision-making document that addresses the following goals:

- examination of the technical and economic feasibility of the project based on an investigation of all parameters and site-specific requirements;
- assessment of technical and economic risks;
- identification of exclusion criteria;
- examination of possible organisational and operational structures;
- creation of a basis for preparation of an application for government subsidy;
- creation of a basis for an assessment of financial viability.

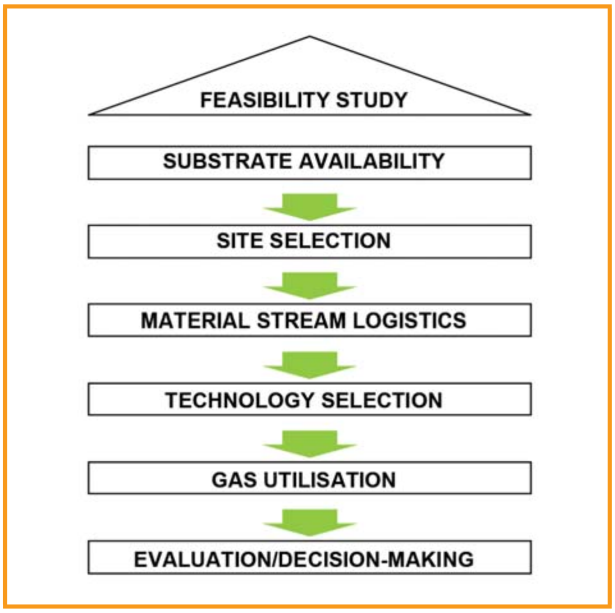

Figure 11.3: Criteria for a feasibility study on a biogas plant

Step 2: Developing the feasibility study	
Engage the services of an experienced and reputable engineering firm/engineering department of an experienced and reputable plant manufacturer	These individuals are extremely important for the further development and planning of the project and will be involved in all further steps. They have access to contacts at permitting authorities and also at regional authorities.
Get in touch with an agricultural adviser	An agricultural adviser is experienced in the building and operation of biogas plants and will be a source of professional advice in connection with other issues, ranging from site selection and plant design through to construction and commissioning.
Decide on the type of plant and construction procedure as well as on the size of plant	Definition of the site characteristics, e.g. ordering of a soil report. Site selection (with reference to a general plan of the farm, buildings, silo areas). Location of the nearest power or gas feed-in point. Decision on appropriate plant configuration/design and technology with reference to future vision for the farm and operational restructuring measures necessitated by the biogas plant. Sizing of the plant components according to an analysis of potentials. Question of procedure: How do I want the project to be implemented? Do I want a turn-key plant? Do I want to break down the plant construction process into a number of separately awarded contracts? How much of the work do I plan to do myself? Can I share the project with other farms? Which contract works do I plan to put out to tender? (e.g. earthworks, electrics…) Leave room for different options.
Goals in Step 2:	- Involvement of an experienced engineering firm or adviser for preparation of a feasibility study - Determination of the preferred size of plant and type of plant/procedure with possible feed-in points for power, heat or processed biogas

11.2.1 Substrate availability

The realisation and operation of a biogas plant are critically dependent on the extent to which substrates can be made available in sufficient quantities on a year-round basis for loading into the plant. This calls for an examination of whether the required substrates can be sourced at acceptable cost. Farms that keep livestock are at an advantage in that they already have low-cost access to substrate (manure) that can be made available at the site of the biogas plant without the need for complex logistics. Moreover, the quality of the manure as a farm fertiliser can be improved by the digestion process (cf. Section 4.1). Conversely, for a crop-producing farm, the availability of substrate will depend exclusively on the available agricultural land as well as on the associated costs of supply [11-1]. The type and availability of substrates will determine the technology required for the biogas plant. A checklist for determining the availability of substrate is provided below.

Step 3: Availability of substrates	
Distinguish between the available substrates	Which biomass substrates are available: - agricultural residues (e.g. cattle manure, poultry excrement) - agroindustrial wastes (e.g. apple mash, pomace) - wastes from trade and industry (e.g. grease trap waste) - wastes from private households (e.g. biowastes) - renewable resources, energy crops (e.g. maize silage, grass silage) At what times will the substrates be available? In what quality will the substrates be supplied?
Biomass suppliers	Who are the potential long-term suppliers of biomass?
Costs of supply	How much will the substrates cost to supply?
Storage area	How much storage area will be required at the planned site?
Pretreatment	How much pretreatment (mixing, comminution) will the envisaged substrates require?
Goals in Step 3	- Selection of substrates with a view to a workable digestion process - Definition of measures for pretreatment and processing of substrates - Selection of potential biomass suppliers

11.2.2 Site selection

When selecting a site on which to construct a biogas plant, it will be necessary to give consideration not only to local site-specific circumstances (such as suitable subsoil, previous use, availability of utilities), which will be reflected particularly in the construction costs, but also to local building-law requirements and social aspects. Site selection criteria for the construction of a biogas plant are presented in diagrammatic form in Figure 11.4.

11.2.2.1 Site-specific aspects

It must first of all be clarified whether the preferred site is of the necessary size, whether the subsoil is suitable and, if possible, free from contamination, whether any existing buildings and storage areas are in a usable condition and whether grid connection points and heat offtakers are available (cf. Section 9.1.1). The purpose of such an assessment is to keep down the construction costs. The relatively low capacities involved in agricultural biogas production and the associated substrate streams allow the supply of substrate and the disposal of digestate to be effected by road transport. Many substrates scarcely merit the cost of transport on account of their relatively low energy density. Consequently, the search for substrates with which to supply the biogas plant will focus on biomass that is available from the immediate regional vicinity. It will be advantageous to select a site that has access to roads of average transport capacity (such as country roads/B-roads) [11-3].

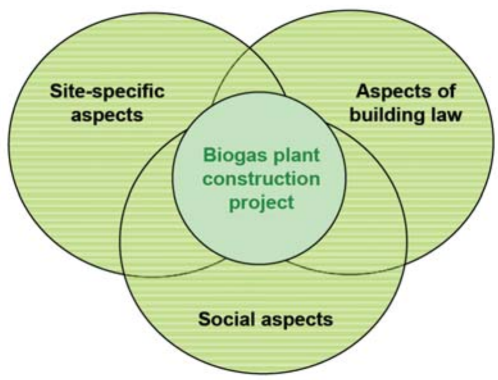

Figure 11.4: Criteria for site selection

11.2.2.2 Aspects of building law

Building law distinguishes between the inner and outer zones of a built-up area. While the inner zone includes all of the land inside a built-up area, the outer zone refers to the land outside the built-up area. This differentiation between inner and outer zones is laid down in the land use plan of the local authority. To avoid fragmentation of the countryside, there are limitations on building in the outer zone. According to Section 35 para. 1 of the building law code (BauGB), the construction of a biogas plant in the outer zone is permitted under certain conditions, in which case such a plant is classed as 'privileged'. Consideration must also be given to any applicable pollution control legislation as well as to possible regulatory conditions concerned with interference with nature and the countryside (such as compensatory measures).

11.2.2.3 Social aspects

Experience suggests that a proposed biogas project – especially in rural areas – may give rise to debate over whether the project meets with the approval of local residents and/or institutions. This issue can have a particularly disadvantageous impact on whether or not a permit is granted for the proposed plant. Especially a fear of negative consequences, such as odour nuisance, noise emissions, increased traffic volume and visual impact of the site, can result in opposition to the planned project among the affected population. Early measures to build up local acceptance, such as a timely information campaign, involvement of affected residents and institutions as well as a targeted PR campaign, are therefore essential for securing approval of a preferred site for a biogas plant.

Step 4: Selecting the site	
Check out the site	What is the site like? Is the subsoil suitable? Is the site in an industrial zone (on the periphery) or on a farm in the outer zone ('privileged')? How high are the land costs?
Check out the infrastructure	Is the road access suitable for trucks? Which utilities (power, water, sewage, telecoms, natural gas) are available at the site?
Check out the site for power feed-in	How far away is the nearest power feed-in point?
Check out the options for heat utilisation	Are there potential heat offtakers near the site? Can the waste heat from the CHP process be used on my own farm? Are the associated conversion works/costs in proportion to the benefit? How much heat needs to be supplied every month? Does the possibility exist to set up a satellite CHP unit (CHP unit physically separate from the biogas plant and connected to the gas tank by a relatively long gas pipeline)?
Check out the options for gas feed-in	Is there a possibility at the site for feeding processed biogas into an existing adjacent natural gas grid? (cf. Section 6.3)
Build up local acceptance	Which local residents and businesses will be affected? Which local residents and businesses need to be informed about the project at an early stage and, where appropriate, involved in the project? Who are the potential heat offtakers? Which public institutions need to be included at an early stage in a transparent PR campaign (e.g. involvement of mayors, permitting authority)? What nature conservation interests need to be addressed?
Goals in Step 4	- Selection of the site - Selection of form of biogas utilisation (CHP unit at the site, setting-up of a satellite CHP unit or processing of biogas for feed-in to the natural gas grid) - Building-up of local acceptance through transparent PR campaign

11.2.3 Material stream logistics

In view of the distributed structure of biomass arisings and the sometimes distributed, sometimes centralised offtaker structure, biomass logistics assumes a key role within the overall supply chain. This encompasses all enterprise- and market-related activities aimed at making a substrate available. The focus is on optimising the stream of materials and information between supplier and offtaker.

The choice of material stream logistic chains as well as the related signing of one or more biomass supply contracts (long-term, if possible) are especially important for a biogas plant, which requires a constant input of substrate throughout the year. Firm agreements should be signed with suitable biomass suppliers, ideally before the plant is constructed. This will allow both the plant itself and the design of the storage areas and storage tanks to be harmonised with the envisaged substrates and delivery intervals at the planning stage, the goal being to balance out any fluctuations in deliveries of biomass substrates to the site. It is important, prior to drawing up the contract, to iron out how substrate deliveries will be billed. Billing is generally according to the delivered quantity/volume of biomass (e.g. in t, m^3). This calls for detailed quality standards and inspections in order to reduce the risk of low-quality substrates.

Substrate treatment (comminution and mixing) and loading of the substrates into the digester are accomplished by means of appropriate metering equipment (screw conveyors), cf. Section 3.2.1. Transport of substrate inside the plant is carried out mainly by electrically operated pumps. The choice of suitable pumps and conveying equipment is highly dependent on the envisaged substrates and degree of treatment.

Presented below is a checklist for analysing the material stream logistics (Step 5).

Step 5: Material stream logistics	
Define and update the material stream volumes	What volumes of substrates do I include in my plans? How wide is the average radius of potential substrate suppliers? How is the seasonal arising of substrates? What are the properties of the envisaged substrates?
Decide on the substrate supply chain	What form of substrate delivery is most efficient for the planned plant? What types of long- and short-term storage are available at the planned site? What forms of treatment and metering will I require? What degree of price uncertainty exists in relation to the purchase of substrates?
Choose the biomass suppliers and digestate offtakers	What substrate delivery terms and quality standards do I need to agree with the relevant biomass suppliers? (e.g. billing of the delivered biomass quantity/volume) Are there offtakers for the digestate?
Substrate transport inside the plant	What handling/transport equipment will I need at the plant? What conveying/pumping equipment will I need inside the plant?
Decide on how the digestate is to be stored	What quantities of digestate will be produced? What method of digestate storage is structurally possible? What method of digestate transport and what digestate field spreading intervals are possible?
Goals in Step 5	- Determination of transport and handling technologies - Definition of available area for substrate and digestate storage at the site of the biogas plant - Selection of biomass suppliers and digestate offtakers - Definition of supply agreements and, if possible, long-term supply contracts

11.2.4 Technology selection

According to state-of-the-art plant engineering suitable for real-world applications, the choice of technology for a planned biogas plant will depend in particular on the available substrates (cf. Section 3), the existing infrastructure, the involved parties and the available financing. Presented below is a checklist for technology selection (Step 6).

Step 6: Selecting the technology	
Select the digestion process	Will the plant use wet or dry digestion or a combination of both? What process stages will the plant use? And at what process temperature?
Select the plant components	What components will the plant use? - Receiving, treatment and loading equipment - Digester with internal components and agitator system - Type of gas tank - Method of digestate storage - Biogas utilisation
Involved parties	Which farms and enterprises will be involved as network partners? What experience do the involved parties have? What installation and maintenance firms are available in the immediate vicinity? How much do my staff and partners know about substrate treatment/loading or about transport/silage equipment?
Goals in Step 6	- Selection of state-of-the-art plant components of high-grade, maintenance-friendly materials with automated operation.

11.2.5 Gas utilisation

Depending on the site specifications and envisaged end use, a decision must be made on how to recover the energy from the produced biogas (cf. Section 6). Presented below is a checklist on energy recovery from the biogas produced by the biogas plant (Step 7).

Step 7: Recovering the energy from the biogas	
Type of biogas utilisation	How can the produced biogas be efficiently used at the site? - Combined heat and power (CHP) generation (e.g. CHP unit, micro gas turbine, etc.) - Cold generation by trigeneration process - Upgrading of biogas (dehumidification and desulphurisation) to natural gas quality for feed-in to the public natural gas grid or micro gas grids - Processing into fuel for motor vehicles - Recovery of heat from biogas
Goals in Step 7:	- Selection of method of energy recovery from biogas

11.2.6 Evaluation and decision-making

Evaluation and decision-making for a biogas project is carried out according to the criteria of profitability and method of financing (cf. Section 8.2). A corresponding checklist can be found below in Step 8: Evaluation and decision-making.

Step 8: Evaluation and decision-making	
Draw up a detailed cost budget	A detailed cost budget can be drawn up based on the selected procedure. The cost budget should allow budgetary control at all times. The cost items should be broken down into the following blocks: - costs of individual components - substrate costs (delivery 'free to digester') - depreciation - maintenance and repair - interest - insurance - labour costs - financing/permitting costs - planning/engineering costs - utility costs, grid connection costs - transport costs (if any) - overheads (telephone, rooms, utilities, etc.) The costs of the individual components should be broken down; you should put a precise figure on any work you intend to carry out yourself and/or on any work you intend to contract out.
Possibility of government subsidy	Alongside the market incentive programme and low-interest loans from KfW (German development bank) at federal level, there are various regional government subsidy programmes in the individual German states. Which subsidy-granting agencies should I write to? What requirements must I meet when applying for/claiming a government subsidy? What time limits must I meet? What documents must I submit?
Financing	The external financing requirement must be calculated. You should avail yourself of the financial advice offered by banks; financing strategies should be subjected to a thorough examination with regard to the situation in which the farm finds itself. Financing proposals should be compared.
Goals in Step 8:	- Preparation of a profitability analysis, taking account of the assessment of other advantages (e.g. odour, flowability of biogas slurry, etc.) Consequence: possible establishing of contact with (neighbouring) farms in order to: - source additional substrates - set up a community of operators → New profitability analysis as a decision-making basis

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Landesabfallgesetz: Regional regulations of German states on collection and recycling of organic wastes (state waste disposal law)

Landeswassergesetz: Regional regulations of German states on Water Resources Act (state water law: Landeswassergesetz – LWG)

TA Lärm: Technical Instructions on Noise Abatement (Sixth General Administrative Regulation on Pollution Control Act)

TA Luft: Technical Instructions on Air Quality Control – TA Luft (First General Administrative Regulation on Pollution Control Act)

UVPG: Environmental Impact Assessment Act

VOB: German construction contract procedures (Vergabe- und Vertragsordnung für Bauleistungen)

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

Wasserhaushaltsgesetz: Water Management Act (Wasserhaushaltsgesetz – WHG)

12 Significance of biogas as a renewable energy source in Germany

For more than 30 years now, debate over energy policy and environmental policy in Germany has been largely driven by energy-related impacts on the environment. Substantial efforts in Germany to push ahead with renewable forms of energy have already led to a significant reduction in emissions of climate-damaging gases. A major contribution in this respect has been made by the supply and utilisation of biogas, especially for the generation of electricity.

Since the Renewable Energy Sources Act (EEG) came into force in 2000, the rate of production and utilisation of biogas has risen sharply, particularly in agriculture. In the past this trend was supported by the German Government's market incentive programme (MAP) and by various investment promotion programmes in the federal states. The amendment of EEG in 2004 played a big part in accelerating the construction of biogas plants. It made the use of energy crops for the supply of biogas an economically attractive proposition, which has led, among other things, to the present situation, in which considerable potential for biogas production and utilisation has already been developed. Nevertheless, there is still appreciable potential for organic material streams to be exploited for the production of biogas. Conditions are thus now in place that offer the prospect of swift further expansion of the production and utilisation of biogas.

12.1 Biogas production as an option for generating energy from biomass

The term 'biomass' refers to matter of organic origin that can be used to supply energy. Biomass thus includes the phytomass and zoomass (plants and animals) living in nature and the waste products they generate (e.g. excrement). Other organic waste matter and residues, such as straw and slaughterhouse waste, are also classed as biomass.

Biomass is generally subdivided into energy crops, harvest residues, organic by-products and wastes. Further details are given in Chapter 4 'Description of selected substrates'. These material streams first have to be made available for energy recovery. In by far the majority of cases this necessitates a transport process. In many instances the biomass has to undergo mechanical processing before energy can be recovered from it. There is often also a need for storage in order to match the arisings of biomass to the demand for energy (Figure 12.1).

Next, heat, power (electricity) and/or fuel can be made available from the biomass. Various technologies can be used for this purpose. One of these is direct combustion in appropriate fuel-burning plants, some of which allow the cogeneration of heat and power. However, the exclusive supply of heat from solid bioenergy sources is the most typical application for generating final/useful energy from biomass.

In addition there is a multiplicity of other techniques and methods that can be used to make biomass available to meet the demand for final/useful energy (Figure 12.1). It is common in this connection to distinguish between thermo-chemical, physico-chemical and biochemical conversion processes. The generation of biogas (anaerobic digestion of substrates to form biogas) is one of the possible options among the biochemical conversion processes.

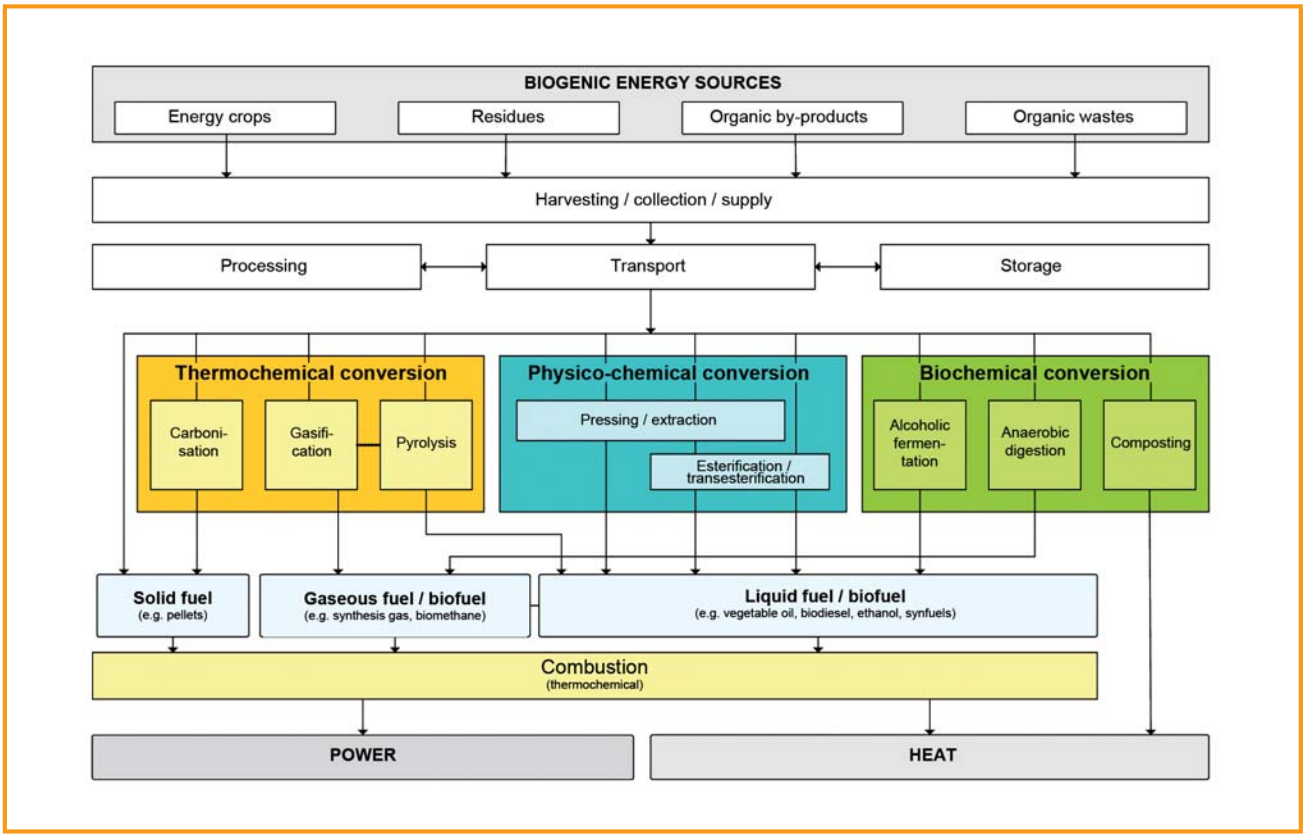

Figure 12.1: Options for utilising biomass for the supply of final energy/useful energy

12.2 Ecological role and sustainability of biogas production and utilisation

Many research and assessment projects are currently being conducted into the ecological role of biogas production and utilisation. The results from some of these projects are already available. It can generally be stated that sustainability is primarily dependent on the choice of substrates, the quality (efficiency and emissions) of the plant technology and the efficiency with which the biogas is utilised.

As far as the input of substrates is concerned, feedstock that incurs no additional expense is often to be considered ecologically beneficial. This is why the use of such substrates for biogas generation should be encouraged. For example, the utilisation of manure in the biogas process not only puts readily available quantities of substrate to meaningful use, but it also avoids the emissions that would otherwise result from the conventional storage of manure. Particular preference should therefore be given to mixtures of residual materials and wastes (e.g. excrement, residues from the food industry), over dedicated energy crops grown specifically for the purpose. In ecological terms, however, residues and wastes can also serve as a highly beneficial supplement for the digestion of energy crops.

With regard to plant technology, great importance should be attached to avoiding emissions and to achieving high levels of efficiency, i.e. ensuring that a high proportion of the biomass is digested. While this may involve structural and design measures at the time of the initial investment, attention should also be paid to the way in which the biogas plant is operated. Further pointers and detailed analyses can be taken, for example, from the reports issued as part of the IFEU project aimed at optimising the sustainable expansion of biogas generation and utilisation in Germany [12-1].

The biogas utilisation concepts that are most beneficial are those that convert as much of the energy contained in the biogas as possible and that, above all, act as substitutes for energy sources that cause high CO_2 equivalent emissions, such as coal or oil. Concepts that include the cogeneration of heat and power, making maximum possible use of the available heat, are therefore generally at an advantage over all other utilisation options. To the maximum possible extent, heat recovery should take the place of fossil fuels as a

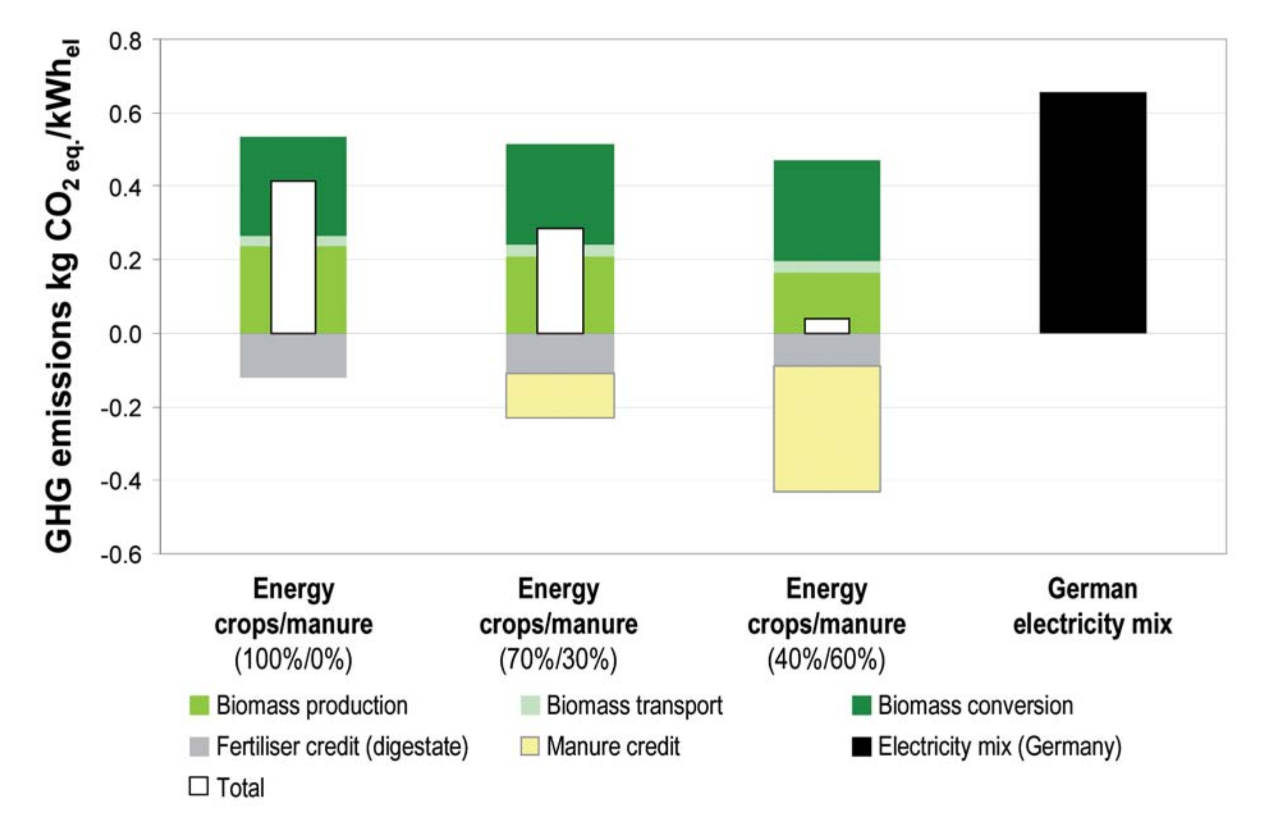

Figure 12.2: Greenhouse gas emissions (kg $CO_{2\ eq.}$/kWh_{el}) from model biogas plants compared with German electricity mix [12-5]

source of heat generation. Especially in the case of relatively large biogas plants, this may not be possible because, for example, the plant is not in a suitable location. In such cases, one option for lessening the environmental impact is to upgrade the biogas to natural gas quality and to feed it through to a location where there is a high year-round demand for heat and where conversion can then take place.

As an example, Figure 12.2 contrasts the greenhouse gas (GHG) emissions from biogas power generation at various biogas plants with the greenhouse gas emissions from the German power mix (2005) [12-5]. The plants in this calculation are model biogas plants, which are assumed to utilise either just energy crops or a mixture of energy crops and manure as feedstock for producing biogas. The GHG emissions are given in kilograms of carbon dioxide equivalent per kilowatt-hour of electricity generated. The growing of energy crops is normally associated with additional climate-relevant emissions (such as nitrous oxide or ammonia), while, where manure is used for energy recovery in biogas plants, there are also emission savings that can be taken into account. Preference should therefore be given to exploiting the economic potential that can be harnessed from animal excrement and residual plant matter from agricultural sources. Thanks to the credits for avoided emissions as a result of digesting the manure as opposed to storing untreated manure, greenhouse gas emissions decline relative to the German power mix as the proportion of manure in the feedstock increases. As well as reducing greenhouse gases as compared with conventional storage of manure (without it being used in a biogas plant), manure also has a process-stabilising effect [12-1]. As digestate can be used as a substitute for mineral fertiliser, it qualifies for fertiliser credits, which likewise has a positive impact on the greenhouse gas balance.

The results show that greenhouse gas emissions can be avoided by producing power from biogas as a substitute for conventional energy sources (in Germany these are mainly nuclear energy and energy from coal or lignite). First and foremost, however, this depends on how the biogas plant is run.

When it comes to an assessment of the data calculated as part of an eco-balance, it should also be stated that the input data for the calculations are often subject to a high degree of uncertainty and are not therefore directly valid for a specific practical application. Furthermore, in most cases it is not the absolute figures that are crucial; in fact it is usually necessary to compare the differences between various options for biogas production and utilisation in order to arrive at an assessment. However, measurements are currently being carried out on modern biogas plants to significantly improve the underlying stock of data, with the consequence that in future the reliability of such statistics will be considerably greater.

12.3 Current status of biogas production and utilisation in Germany

This section discusses the status of biogas production and utilisation in Germany as at March 2010. The descriptions relate to biogas plants, not including landfill sites and sewage gas plants.

12.3.1 Number of plants and plant capacity

The number of biogas plants in Germany has steadily grown since the Renewable Energy Sources Act (EEG) came into force. This Act should therefore be seen as a successful instrument for the biogas sector. It is above all the fact that a reliable framework has been put in place for the long term that has contributed to this positive trend. The amendment of EEG in 2004 was particularly significant, when promotion of the use of energy crops in biogas plants was included in the Act. Figure 12.3 illustrates that the number of plants has grown notably since 2004, as has the average plant's installed electrical capacity. The greater use of energy crops has paved the way for this increase in the average capacity of biogas plants. At the end of 2008 the average capacity of a biogas plant was roughly 350 kW_{el} (for comparison, the figure for 2004 was 123 kW_{el} [12-3]). By the end of 2009, average plant capacity in Germany had risen to 379 kW_{el} [12-7]. In contrast with plants added before the 2009 amendment of EEG, newly built plants in 2009 were in the range < 500 kW_{el}. Most new plants are in the capacity range between 190 and 380 kW_{el}.

At the end of 2009 there were around 4,900 biogas plants in existence, with an installed electrical capacity of approximately 1,850 MW_{el}. Compared with the rather slow rate of construction of new biogas plants in 2008, new build soared in 2009, adding some 900 new plants with an installed capacity of around 415 MW_{el}. This is largely attributable to the 2009 amendment of EEG and to the significantly improved rates of remuneration for electricity generated from biogas. The observable trend is therefore very similar to the one that followed the 2004 amendment of EEG. The potential amount of power generated from biogas in 2009 is estimated at roughly 13.2 TWh_{el}[1] [12-3]. Allowing for the fact that construction of new plants in 2009 was spread over the whole year, the real level of power generation from biogas is likely to be lower, it being reasonable to assume an output of around 11.7 TWh_{el}[2] [12-3]. This is equivalent to about 2% of total gross power generation in Germany, which, according to provisional estimates, amounted to 594.3 TWh_{el} [12-2] in 2009.

Table 12-1 lists the number of biogas plants in operation in each of the federal states and in Germany as a whole at the end of 2009, as well as the total installed electrical capacity and the average capacity per plant. The data originate from a survey of the ministries of agriculture and/or environment, chambers of agriculture and agricultural research institutes in the respective states.

The high average electrical plant capacity for Hamburg is attributable to the biowaste plant installed there, which has a capacity of 1 MW_{el}. No biogas plants were recorded for the city states of Berlin and Bremen, apart from wastewater treatment plants with utilisation of the gas they generate.

Figure 12-4 shows the installed electrical capacity in relation to the area of agricultural land [kW_{el}/1,000 ha] in the individual federal states.

In addition, at the end of 2009 about 31 plants were in operation that feed biogas into the natural gas grid; these had an installed gas capacity totalling around 200 MW. The actual level of gas injection into the natural gas grid for 2009 was forecast at roughly 1.24 TWh, because different commissioning dates and degrees of capacity utilisation at the various plant sites need to be taken into account. Furthermore, at some plant sites, instead of biogas being fed into the natural gas grid, it is converted into electricity on site, while at one plant the biogas is used directly as a vehicle fuel. It is expected that further biogas feed-in plants will be commissioned.

1. Potential power generation based on an average 7,500 full-load hours per year, not taking account of the date of commissioning of new plants.
2. To estimate the real amount of power generated from biogas, the following assumptions were made: 7,000 full-load hours for plants in operation before the end of 2008; 5,000 full-load hours for new plants added in the first half of 2009, and 1,600 full-load hours for new plants added in the second half of 2009.

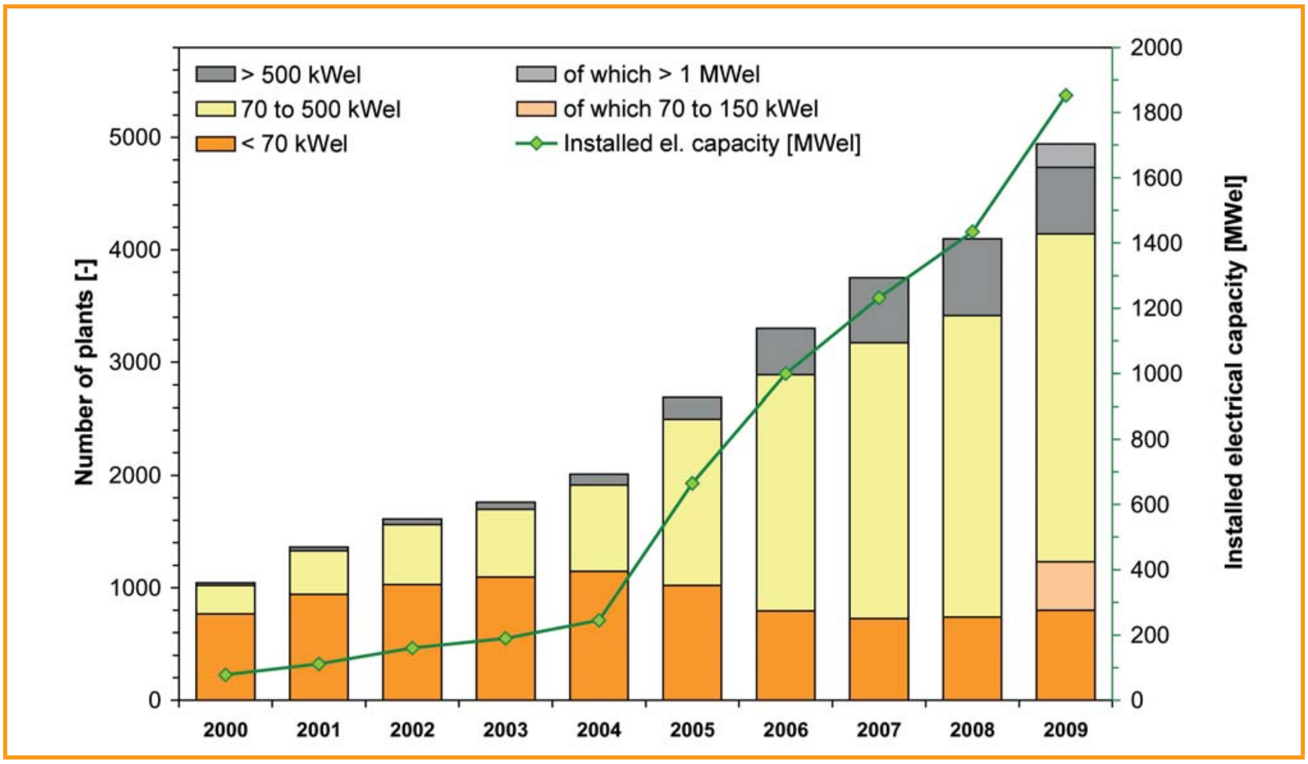

Figure 12.3: Growth in construction of biogas plants in Germany to 2009 (number of plants differentiated by capacity class and installed electrical plant capacity in MW_{el}) [12-3]

Table 12.1: Regional distribution of biogas plants in operation in Germany in 2009 and installed electrical capacity of the plants (survey of state institutions conducted in 2010) [12-3]

Federal state	Number of biogas plants in operation [units]	Total installed capacity [MW_{el}]	Average plant capacity [kW_{el}]
Baden-Württemberg	612	161.8	264
Bavaria	1,691	424.1	251
Berlin	0	0	0
Brandenburg	176	112.0	636
Bremen	0	0	0
Hamburg	1	1.0	1,000
Hesse	97	34.0	351
Mecklenburg-Western Pomerania[a]	156 (215)	116.9	544
Lower Saxony	900	465.0	517
North Rhine-Westphalia	329	126.0	379
Rhineland-Palatinate	98	38.5	393
Saarland	9	3.5	414
Saxony	167	64.8	388
Saxony-Anhalt	178	113.1	635
Schleswig-Holstein	275	125.0	454
Thuringia	140	70.3	464
Total	4,888	1,853	379

a. Number of operational sites, with plant parks being combined and counted as one site because of modified data collection methodology. Figure in brackets: estimated number of biogas plants

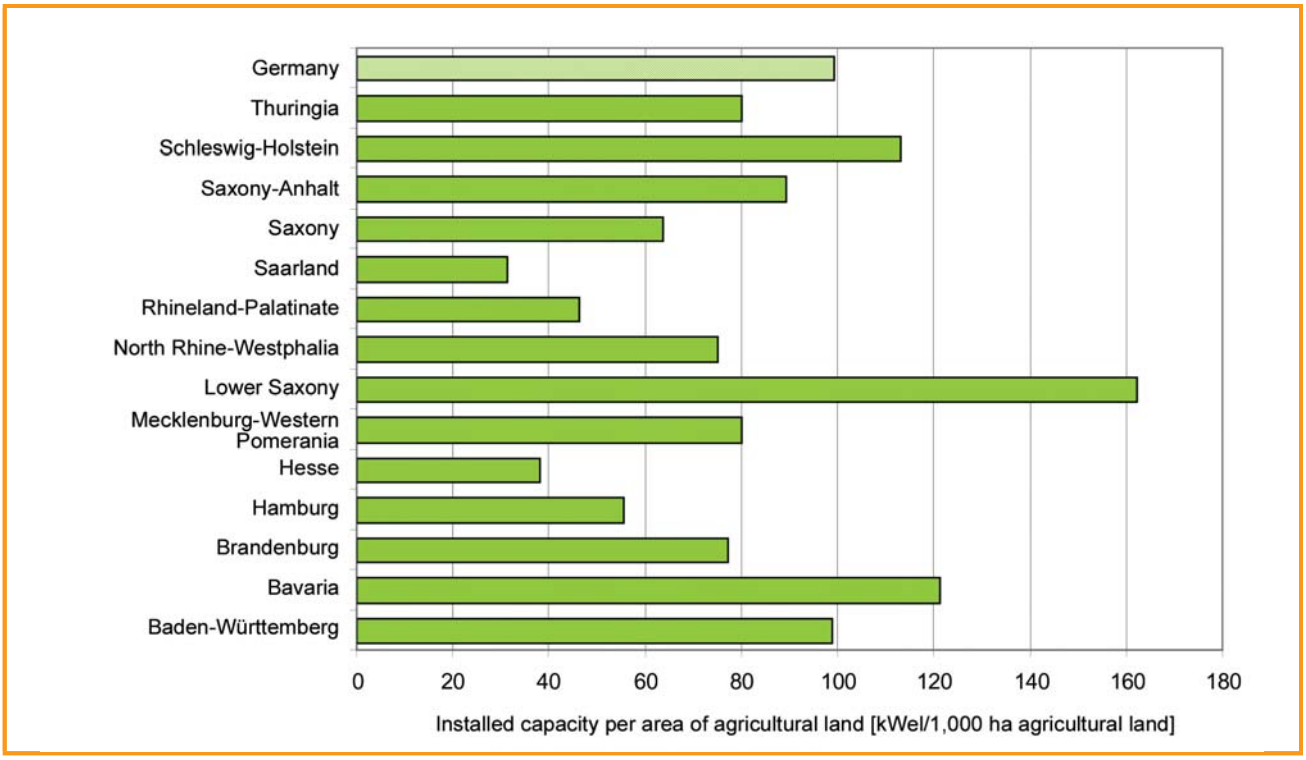

Figure 12.4: Installed electrical capacity in relation to the area of agricultural land [kW_{el}/1,000 ha agricultural land] in the German federal states (based on data from [12-3], [12-6])

12.3.2 Biogas usage and trends

The amendment of EEG in 2009 introduced significant incentives for the further expansion of biogas capacities. Given the tariff structure established under EEG it is expected that there will once again be a stronger trend towards relatively small biogas plants (< 150 kW_{el}), although the construction of additional larger biogas plants will also be continued. The generation of electricity from biogas/biomethane after transmission through the natural gas grid will remain a key priority.

In plants where biogas is intended to be used to generate electrical energy, it is becoming increasingly important in terms of both energy efficiency and economic profitability to put the heat from CHP units to practical use, if possible without wastage. Unless there is a potential heat sink in the immediate vicinity of the plant, the CHP unit can be installed close to where the heat will be used. The CHP unit can either be supplied via the natural gas grid with biogas that has been upgraded to natural gas quality (including carbon dioxide removal), or it can be supplied with dehydrated and desulphurised biogas through micro gas networks.

Upgrading biogas to natural gas quality for injection into a grid is therefore likely to continue to become more widespread. Apart from power generation, there will also be scope for utilising the available biomethane to provide heat and motor vehicle fuel. This flexibility of its potential use is a major advantage for biomethane over other energy sources. As far as the supply of heat is concerned, (apart from relatively small wastewater treatment plants where biogas is used in industrial processes to provide process heat) future developments will largely depend on the willingness of customers to purchase biomethane, which is slightly more expensive than natural gas, and on any future changes to the legal framework. With regard to utilisation as vehicle fuel, the basis for future trends is currently an undertaking by the German gas industry to substitute 10% of natural gas sold as vehicle fuel with biomethane by 2010, with this figure rising to 20% from 2020 onwards.

12.3.3 Substrates

In Germany, most of the base substrate used at present – in terms of substrate mass – comprises excrement and dedicated biomass crops. The results of an operator survey from 2009 on mass-based substrate input (fresh mass) in biogas plants, founded on the answers given in 420 questionnaires, are shown in Figure 12.5 [12-3]. According to this survey, in terms of mass, 43% of substrate is excrement and 41% energy crops, while the proportion of biowastes is roughly 10%. Because of different statutory regulations in Germany, biowastes are mostly treated in specialised waste digestion plants. At around 6%, industrial and agricultural residues make up the smallest proportion of the substrates used. The use of agricultural residues has not risen as expected, despite the fact that new provisions in EEG 2009 mean that selected agricultural residues (cf. EEG 2009, Annex 2, Section V) can be supplied to biogas plants without this resulting in the loss of the energy crop bonus.

In terms of energy content, energy crops are currently the dominant type of substrate in Germany. This makes Germany one of the few European countries that obtain most of their primary energy production from biogas from sources (such as distributed agricultural plants) other than landfill gas and sewage gas [12-4] (reference year 2007).

The use of energy crops as a substrate is common practice in 91% of all agricultural biogas plants [12-3]. In terms of volume, silage maize dominates the market among energy crops (see also Figure 12.6), although almost all biogas plants utilise several different energy crops at the same time, including, for example, whole-crop cereal silage, grass silage or cereal grains.

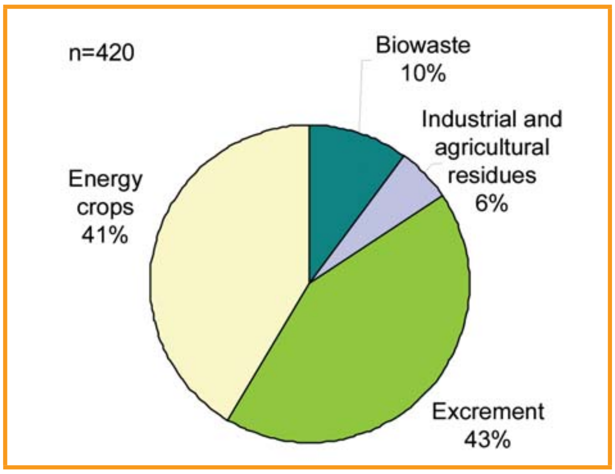

Figure 12.5: Mass-based substrate input in biogas plants (operator survey 2009) [12-3]

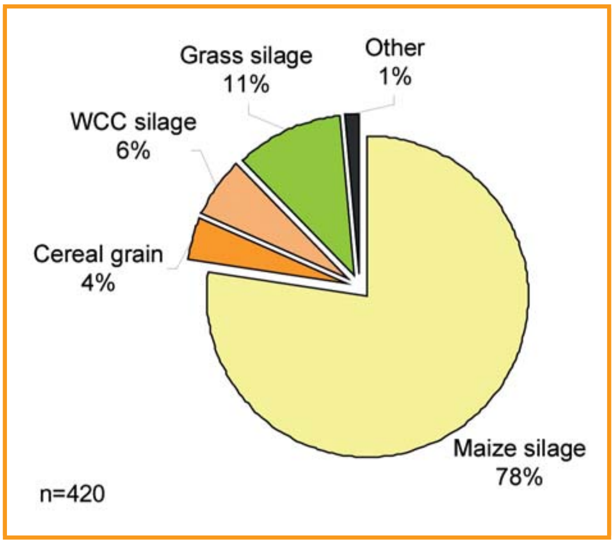

Figure 12.6: Mass-based use of energy crops as substrate in biogas plants (operator survey 2009) [12-3]

Since 2004 it has increasingly been the case that plants have been run exclusively on energy crops without excrement or other co-substrates. Thanks to the use of digestion aids, such as mixtures of trace elements, it has now become possible to maintain microbiologically stable operation.

Details of the various substrates are given in Chapter 4, Description of selected substrates.

12.4 Potential

Determination of the present potential for biogas production and forecasting of future production depends on a variety of factors. In the agriculture sector, the factors determining the potential include the prevailing general economic conditions, the cropping structure and the global food situation. There are many different areas competing for biomass from agriculture, ranging from food production (including animal feed) to utilisation for the production of materials or the generation of energy, which, in turn, have various competing conversion pathways. Similarly, a wide variety of material utilisation pathways or energy recovery routes are available for residues from agriculture, municipal authorities and industry. Consequently, the outcomes of forecasts are likely to differ widely, depending on the assumptions made.

12.4.1 Technical primary energy potential

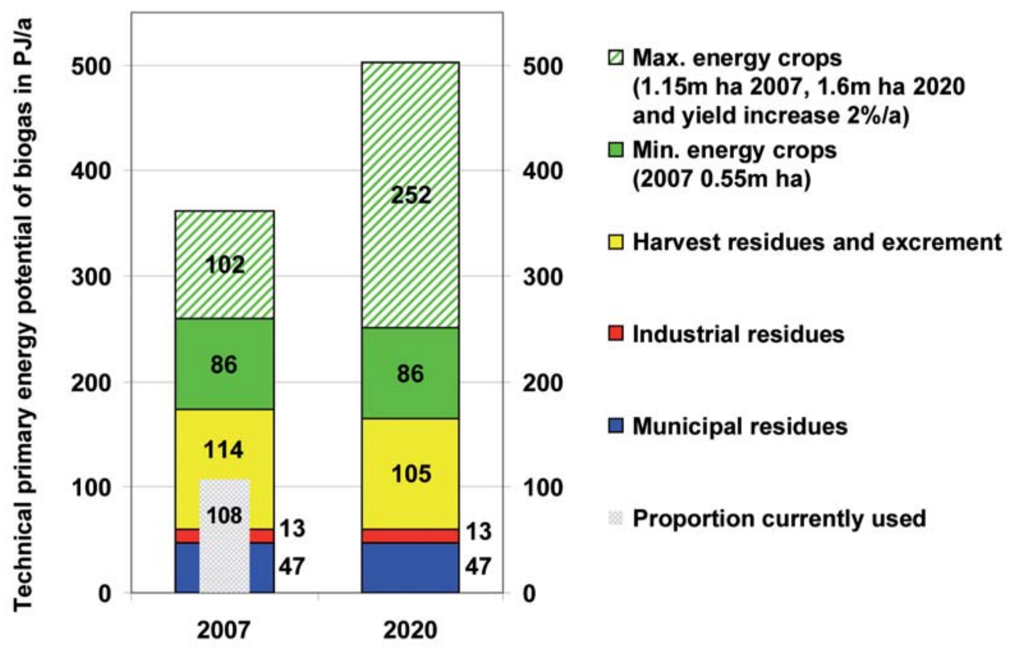

Figure 12.7: Technical primary energy potential for biogas in Germany in 2007 and 2020

Biogas can be produced from a whole range of different material streams. This section therefore examines the technical primary energy potentials of the various material streams under consideration as well as the corresponding technical generation potentials (supply of power and/or heat) and final energy potentials[1] (i.e. the final energy available for use in the energy system) with reference to the various potentially usable biomass fractions. The substrates have been divided into the following groups:

- municipal residues
- industrial residues
- harvest residues and excrement
- energy crops: grown on an area of about 0.55 million ha in Germany (2007) for biogas production, representing the minimum potential
- energy crops: grown on a total area of 1.15 million ha in Germany (2007)/1.6 million ha (2020) for biogas production, representing the maximum potential.

The technical primary energy potential in Germany for biogas from municipal residues and from industrial residues is calculated at 47 PJ/a and 13 PJ/a respectively (Figure 12.7). By far the greatest potential at present, and according to current forecasts also in future, is to be found in the agriculture sector (including harvest residues and excrement), despite the fact that the predicted trend is for a slight decline from 114 PJ/a in 2007 to 105 PJ/a in 2020. There are significantly wider variations of biogas potential in areas used for dedicated biomass crops, as the land available for growing energy crops may be in competition with other (energy-related) utilisation options. Therefore, both a minimum and a maximum figure is shown for the biogas potential from energy crops.

In 2007 in Germany, the technical primary energy potential of energy crops grown exclusively for energy production was roughly 86 PJ/a, with an area under cultivation of around 0.55 million ha for biogas

1. The technical potential of a renewable energy source is the proportion of the theoretical potential that is available for use after allowance has been made for the existing technical restrictions. In addition, it is generally necessary to take account of structural and ecological restrictions (e.g. nature reserves or areas designated for the planned networking of biotopes in Germany) and statutory requirements (e.g. whether organic wastes that pose potential health concerns are admissible for use in biogas plants), because, ultimately, these restrictions are often 'insurmountable' – similar to the (exclusively) technical restrictions. With regard to the reference quantity for energy, a distinction can be drawn between the following:
· technical primary energy potentials (e.g. the biomass available for production of biogas),
· technical production potentials (e.g. biogas at the output of a biogas plant),
· technical final energy potentials (e.g. electrical energy from biogas plants at the end user) and
· technical final energy potentials (e.g. energy of the hot air from a hair dryer powered by electrical energy from a biogas plant).

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production alone.[1] If it is assumed that a maximum of 1.15 million ha is available for biogas production, this potential rises by 102 PJ/a for 2007.

Assuming that approximately 1.6 million ha of cultivation area is available in 2020 for biogas use and that there is an annual increase in yield of 2%, the technical primary energy potential from dedicated biomass crops for biogas production can be expected to total 338 PJ/a.

With regard to how much of the biogas potential is actually utilised, it is assumed that about 108 PJ was used for biogas production in 2007. This is equivalent to roughly 42% of the predicted biogas potential based on minimum energy crop use (0.55 million ha) and to roughly 30% based on maximum energy crop use (1.15 million ha).

12.4.2 Technical final energy potentials

The production potentials outlined above can be converted into heat and/or electricity. The production potentials identified in the following describe the producible heat/power without consideration of demand-side restrictions as well as the final energy potentials with consideration of demand-side restrictions. Thus, the final energy potentials most accurately reflect the contribution made by biogas production and utilisation to meeting the demand for final or useful energy.

12.4.2.1 Generation of power

Given a conversion efficiency of around 38% for power generation in engines or combined heat and power (CHP) units, the demonstrated production potential can be used to calculate a potential electricity production and thus a technical final energy potential of max. 137 PJ/a for 2007. If an average electrical efficiency of 40% is assumed for 2020, current estimates point to a maximum technical final energy potential of 201 PJ/a.

12.4.2.2 Supply of heat

With a conversion efficiency of 90% for the supply of heat alone, a potential heat production or final energy potential of 325 PJ/a is calculated for 2007. If, on the other hand, it is assumed that biogas is used exclusively in CHP units for cogeneration of heat and power and if it is further assumed that the thermal efficiency is 50%, the technical final energy potential for heat alone is calculated as 181 PJ/a for 2007.

12.5 Outlook

The technical potentials for biogas production in Germany, which are largely in the agriculture sector, continue to be considerable and of relevance within the energy industry. Although the big expansion of biogas production and utilisation in recent years has led to a significant reduction in the still available potentials, such that the search for sites for biogas plants has in some cases become more difficult, there is, all in all, still potential available in the agriculture sector to allow further expansion of the use of biogas. The utilisation of biogas as an energy source has clearly improved in recent years as a result of the incentive effect of the Renewable Energy Sources Act relating to the utilisation of waste heat (CHP), to such an extent that today, in addition to electric power, more than a third of the available heat energy contributes to the substitution of fossil energy sources. In particular, it is now rare to build a new plant without it having a comprehensive heat utilisation concept. Older plants, however, still have a relevant potential in terms of unutilised waste heat; efforts should be made in future to exploit this potential.

The plant technology used to harness these potentials has now reached a very high standard – in line with enhanced requirements imposed by the regulatory authorities – which often bears comparison with industrial plants in other sectors. The plants have become significantly more reliable and safer to operate. Regular reports in the press about accidents at biogas plants are more likely to be attributable to the fact that there are now a large number of biogas plants in Germany, with some of them not having been constructed in accordance with the usual requirements, rather than this having anything to do with the quality of the the average plant. There is still scope for most system components to be improved. Often, such improvements should be made with regard to plant efficiency.

Fundamentally, the production and utilisation of biogas is highly preferable in ecological terms to the use of fossil fuels as a means of energy supply. The advantages are particularly clear where residues and waste materials can be converted into biogas at no additional expense. With that in mind, special atten-

1. For the sake of simplicity, the calculation of biogas potential for energy crops assumes that the land is planted with maize. In practice, a mix of energy crops is used in biogas plants (see Chapter 12.3.3), the proportion of maize in the energy crop feedstock in biogas plants being roughly 80% (with respect to fresh mass).

tion should be paid to using biogas efficiently and as completely as possible.

The number of biogas plants in operation has increased more than fivefold in Germany over the past ten years. The total capacity of the plants rose from about 45 MW_{el} in 1999 to 1,853 MW_{el} by the end of 2009, with the average installed electrical capacity per plant having increased from 53 to 379 kW_{el}. It can be assumed that this trend will continue, albeit at a somewhat reduced rate.

While it is true that there are still optimisation issues to be resolved, the production and utilisation of biogas is a mature and marketable technology. It can be seen as a highly promising option for harnessing renewable energy sources that will make a growing contribution to sustainable energy supplies in the coming years, as well as to a reduction in greenhouse gas emissions. This guide is intended to play a part in furthering this trend.

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Glossary

ammonia (NH_3) Nitrogenous gas arising from the degradation of nitrogen-containing compounds such as protein, urea and uric acid.

anaerobic degradability [1] Degree of microbial conversion of substrates or co-substrates, generally expressed as biogas generation potential.

anaerobic microorganisms [3] Microscopic organisms that grow in the absence of oxygen; for some, the presence of oxygen can be lethal.

anaerobic treatment [1] Biotechnological process taking place in the absence of air (atmospheric oxygen) with the aim of degrading organic matter to recover biogas.

biodegradation [5] Breaking down of organic matter, e.g. plant and animal residues, into simpler compounds by microorganisms.

biogas [1] Gaseous product of digestion, comprising primarily methane and carbon dioxide, but which, depending on substrate, may also contain ammonia, hydrogen sulphide, water vapour and other gaseous or vaporisable constituents.

biogas plant [4] Plant designed for the production, storage and utilisation of biogas, including all equipment and structures required for operation of the plant; gas is produced from the digestion of organic matter.

C:N ratio [6] Mass ratio of total carbon to total nitrogen in organic matter; a determining factor in biodegradation.

carbon dioxide (CO_2) [5] Colourless, non-combustible, mildly sour-smelling, intrinsically non-toxic gas formed along with water as the end product of all combustion processes;
concentrations of 4-5% in air have a numbing effect, while concentrations of 8% or over can cause death from asphyxiation.

co-substrate [1] Raw material for digestion, albeit not the raw material accounting for the largest percentage of the material stream to be digested.

combined heat and power (CHP) unit Unit for the conversion of chemically bound energy into electrical and thermal energy on the basis of an internal combustion engine coupled to a generator.

combined heat and power (cogeneration) Simultaneous conversion of input energy into electrical (or mechanical) energy and heat for energy-related use (useful heat).

condensate Biogas produced in the digester is saturated with water vapour and must be dehydrated before being used in a CHP unit. Condensation takes place either via an appropriate underground pipe into a condensate separator or by drying of the biogas.

degree of degradation [1] Extent to which the initial concentration of organic matter in the substrate is reduced as a result of anaerobic degradation.

desulphurisation Physico-chemical, biological or combined method of reducing the hydrogen sulphide content in biogas.

digestate Liquid or solid residue from biogas production containing organic and inorganic constituents.

digestate storage tank (liquid-manure pond) [4] Tank or pond in which liquid manure, slurry or digested substrate is stored prior to subsequent use.

digester (reactor, digestion tank) [4] Container in which a substrate is microbiologically degraded and biogas is generated.

dry matter (DM) content	Moisture-free content of a mixture of substances after drying at 105 °C. Also referred to as total solids (TS) content.
emissions	Gaseous, liquid or solid substances entering the atmosphere from a plant or technical process; also includes noise, vibration, light, heat and radiation.
energy crops [5]	Collective term for biomass utilised for energy-related purposes (not fodder or food). As a rule these are agricultural raw materials such as maize, beet, grass, sorghum or green rye that are ensiled before being put to use for energy-related purposes.
final energy source [7]	A final energy source is the form of energy used by the end user, where the final energy is the energy content of the final energy source or corresponding energy flows. Examples include heating oil in the end user's oil tank, wood chips prior to loading into a furnace, electrical energy in a domestic household, or district heat at a building heat transfer station. It is derived from secondary or sometimes primary energy sources/forms of energy, less the conversion losses, distribution losses, energy consumed for conversion to final energy, and non-energy-related consumption. The final energy source is available for conversion into useful energy.
full-load hours	Period of full utilisation of a plant's capacity; the total hours of use and average utilisation factor over a year are converted to a utilisation factor of 100%.
gas dome [4]	Cover on a digester in which biogas is collected and drawn off.
gas storage tank [4]	Gas-tight vessel or plastic sheeting sack in which biogas is held in temporary storage.
gas store [4]	Room or area in which the gas storage tank is located.
grease trap	Installation for the physical separation of non-emulsified organic oils and fats contained in (for example) wastewater from restaurants, canteen kitchens, slaughterhouses and processing plants in the meat and fish industry, margarine factories and oil mills (cf. DIN 4040).
hydrogen sulphide (H_2S) [4]	Highly toxic, colourless gas with a smell of rotten eggs; can be life-threatening even in low concentrations. From a certain concentration the sense of smell is deadened and the gas is no longer perceived.
hygienisation	Additional process step that may be required to reduce/eliminate pathogens/phytopathogens (disinfection). (see also Ordinance on Biowastes or Regulation [EC] 1774/2002)
marketing	Offering for sale, stocking or any form of distribution of products to others; a term from the Fertiliser Ordinance (DüMV) and elsewhere.
methane (CH_4) [8]	Colourless, odourless and non-toxic gas; its combustion products are carbon dioxide and water. Methane is one of the most significant greenhouse gases and is the principal constituent of biogas, sewage treatment gas, landfill gas and natural gas. At concentrations of 4.4 vol. % or over in air it forms an explosive gas mixture.
nitrogen oxide [8]	The gases nitrogen monoxide (NO) and nitrogen dioxide (NO_2) are referred to collectively as NO_x (nitrogen oxides). They are formed in all combustion processes as a compound of atmospheric nitrogen and oxygen, but also as a result of oxidation of nitrogenous compounds contained in the fuel.
organic loading rate [1]	Amount of substrate fed into a digestion plant per day in relation to the volume of the digester (unit: kg VS/(m^3 ·d))
potentially explosive atmosphere[4]	Area in which an explosive atmosphere may occur due to local and operational conditions.
preparation	Process step for the treatment of substrates or digestates (e.g. comminution, removal of interfering substances, homogenisation, solid/liquid separation).
primary energy source [7]	Materials or energy fields that have not been subjected to technical conversion and from which secondary energy or secondary energy carriers can be obtained either directly or through one or more conversion stages (e.g. coal, lignite, crude oil, biomass, wind power, solar radiation, geothermal energy).
retention time [1]	Average holding time of the substrate in the digester. Also referred to as dwell time.
secondary energy source [7]	Energy source made available from the conversion, in technical installations, of primary energy sources or other secondary energy sources or forms of secondary energy, e.g. petrol, heating oil, electrical energy. Subject to conversion and distribution losses, among others.
silage	Plant material conserved by lactic acid fermentation.
siloxanes [9]	Organic silicon compounds, i.e. compounds of the elements silicon (Si), oxygen (O), carbon (C) and hydrogen (H).
solids infeed	Method of loading non-pumpable substrates or substrate mixtures directly into the digester.
substrate [1]	Raw material for digestion or fermentation.

sulphur dioxide (SO_2) [5]	Colourless, pungent-smelling gas. In the atmosphere, sulphur dioxide is subjected to a number of conversion processes which may result in the formation of various substances including sulphurous acid, sulphuric acid, sulphites and sulphates.
throughput	Depending on definition, this is either a volumetric flow rate or a mass flow rate.
U-value (formerly k-value)[8]	Measure of the heat flow through one square metre of a building element at a temperature difference of 1 Kelvin. The lower the U-value, the lower the heat losses.
volatile solids (VS) content	The volatile solids content of a substance is what remains after the water content and inorganic matter have been removed. It is generally determined by drying at 105 °C and subsequent ashing at 550 °C.
waste management [2]	According to the Product Recycling and Waste Management Act (KrW-AbfG), waste management comprises the recycling and disposal of waste.
waste, general	Residues from production or consumption which the holder discards, intends to discard or is required to discard.

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List of abbreviations

ASUE	Arbeitsgemeinschaft für sparsamen und umweltfreundlichen Energieverbrauch e. V. (Association for the Efficient and Environmentally Friendly Use of Energy)
ATB	Institut für Agrartechnik Bornim e.V. (Leibniz Institute for Agricultural Engineering Potsdam-Bornim)
ATP	adenosine triphosphate
BGP	biogas plant
BImSchG	Pollution Control Act
BioAbfV	Ordinance on Biowastes
C	carbon
C:N	carbon-to-nitrogen ratio
CA	crude ash
CCM	corn cob mix
CF	crude fibre
CH_4	methane
CHP	combined heat and power
CL	crude lipids
Co	cobalt
CO_2	carbon dioxide
COD	chemical oxygen demand
CP	crop production
CP	crude protein
d	day
DBFZ	Deutsches Biomasseforschungszentrum gGmbH
DC	dairy cow
DC	digestibility coefficient
DD	dry digestion
DM	dry matter
DVGW	Deutsche Vereinigung des Gas- und Wasserfaches e. V. (German Technical and Scientific Association for Gas and Water)
EEG	Renewable Energy Sources Act
el	electric(al)
EU	European Union
Fe	iron
FM	fresh mass
FNR	Fachagentur Nachwachsende Rohstoffe e. V.
g	gram
GEM	ground ear maize
GHG	greenhouse gas
H_2S	hydrogen sulphide
ha	hectare
HRT	hydraulic retention time
incl.	including
K	Kelvin
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V. (Association for Technology and Structures in Agriculture)
l	litre
M	model plant
MFE	mineral fertiliser equivalent
Mg	magnesium
Mn	manganese
Mo	molybdenum
N	nitrogen
n.s.	not specified
NADP	nicotinamide adenine dinucleotide phosphate
NawaRo	German abbreviation for nachwachsender Rohstoff; approximately equivalent to energy crops in the context of this document
NFE	nitrogen-free extract
NH_3	ammonia
NH_4	ammonium
Ni	nickel
O	oxygen
OLR	organic loading rate

P	phosphorus
ppm	parts per million
rpm	revolutions per minute
S	sulphur
Se	selenium
TA	Technische Anleitung (Technical Instructions)
th or therm.	thermal
TS	total solids
VOB	Vergabe- und Vertragsordnung für
vol.	volume
VS	volatile solids
vTI	Johann Heinrich von Thünen Institute
W	tungsten
WCC silage	whole-crop cereal silage
WEL	workplace exposure limit (formerly MAC value)

Addresses of institutions

University of Natural Resources and Life Sciences, Vienna (BOKU)
Department of Sustainable Agricultural Systems
Peter-Jordan-Str. 82
1190 Vienna
Austria
Internet: www.boku.ac.at

Johann Heinrich von Thünen Institute (vTI)
Institute for Agricultural Technology and Biosystems Engineering
Bundesallee 50
38116 Braunschweig
Germany
Internet: www.vti.bund.de

Deutsches BiomasseForschungsZentrum gGmbH (DBFZ)
Bereich Biochemische Konversion (BK)
Torgauer Strasse 116
04347 Leipzig
Germany
Internet: www.dbfz.de

Bayrische Landesanstalt für Landtechnik (LfL)
Institut für Ländliche Strukturentwicklung, Betriebswirtschaft und Agrarinformatik
Menzingerstrasse 54
80638 Munich
Germany
Internet: www.lfl.bayern.de

Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)
Bartningstr. 49
64289 Darmstadt
Germany
Internet: www.ktbl.de

PARTA Buchstelle für Landwirtschaft und Gartenbau GmbH
Rochusstrasse 18
53123 Bonn
Germany
Internet: www.parta.de

Thüringer Landesanstalt für Landwirtschaft (TLL)
Naumburger Str. 98
07743 Jena
Germany
Internet: www.thueringen.de/de/tll

Rechtsanwaltskanzlei Schnutenhaus & Kollegen
Reinhardtstr. 29 B
10117 Berlin
Germany
Internet: www.schnutenhaus-kollegen.de

Publisher

Fachagentur Nachwachsende Rohstoffe e.V. (FNR)
OT Gülzow • Hofplatz 1
18276 Gülzow-Prüzen
Germany
Phone: +49 38 43 / 69 30 - 0
Fax: +49 38 43 / 69 30 - 102
info@fnr.de • www.fnr.de

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