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Edited by Arthur Wellinger, Jerry Murphy
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Foreword

As Editor of *BioCycle* and a founding member of the American Biogas Council, I have had a front-row seat to watch the emergence of the anaerobic digestion industry in North America, as well as around the world. Anaerobic digestion as a biological process to treat organic waste streams and produce valuable by-products has been practiced for hundreds of years, if not longer. What is new, relatively speaking, is employing this biological process at a more 'industrial' scale to manage a wide range of organic wastes and meet energy needs of communities. Today, thousands of anaerobic digestion facilities are successfully processing millions of tons of municipal, agricultural and industrial organics, generating electricity, heat, renewable natural gas and biomethane, as well as high-value soil products and plant nutrients.

Reaching this point has only been possible by applying both fundamental principles and advanced research and practice, along with technologies and systems that have evolved in sophistication based on the knowledge gained. *The biogas handbook: Science, production and applications* captures that knowledge in its 19 chapters – beginning with the fundamentals in Part I, discussing plant design, operation, process optimization and digestate utilization in Part II and focusing on biogas utilization in Part III.

To help establish and grow the anaerobic digester biogas industry in the USA, many have spent time touring facilities in Europe and, more recently, the UK. Much knowledge has been gained from the European biogas experience, but the lack of a federal renewable energy policy and incentives has stymied digester project implementation in the USA. Still, there has been steady growth in digester projects, primarily in the agricultural sector. A small number of municipalities and private developers are moving ahead with facilities to digest the organic fraction of municipal solid waste. And more municipal wastewater treatment plant digesters are adding infrastructure to codigest substrates such as food waste and fats, oils and grease to boost biogas production. In all instances, process optimization, as

discussed in Part II of this book, is extremely important for proper management of digesters.

While reading a draft of *The biogas handbook*, I was struck by the following statement in Chapter 6, 'Optimisation of biogas yields from anaerobic digestion by feedstock type,' by Charles Banks and Sonia Heaven with Southampton University in the UK: 'We have to overcome the idea that an anaerobic digester is a rudimentary low-technology waste treatment and disposal system, and replace it with one of a process capable of delivering the multiple benefits of low-cost second-generation renewable energy production, a sustainable route to nutrient recycling and a means of abating GHG emissions'. This statement highlights the role that anaerobic digestion as a technology, and anaerobic digestion as a renewable energy supplier, play in meeting global demand for soil nutrients and organic matter, and for a stable and steady supply of renewable electricity, heat, gas and fuel.

The extent and depth of knowledge and experience captured in *The biogas handbook* will help the emerging anaerobic digestion and biogas industries construct and operate state-of-the-art (and science) biogas plants. As an Editor, I am impressed with the handbook's ability to convey technical and scientific information in a style that can be understood by individuals with varying levels of knowledge about the topics discussed.

Since 1960, *BioCycle* has been promoting practices and technologies that, at their core, conserve the world's resources while sustaining communities and economies. Anaerobic digestion has a unique role because the process and the products service a community's waste management, energy, soil health, water quality and greenhouse gas reduction needs. How to optimize the technology to maximize the quality and quantity of the outputs is at the heart of *The biogas handbook*.

Nora Goldstein
Editor, *BioCycle*

Preface

Biogas is formed naturally from biogenic matter, indeed all forms of biomass, under anaerobic conditions. This naturally occurring biogas escapes into the atmosphere where its main component, methane, is a significant contributor to global warming. Over the last century, methane has become one of the most used fuels for power generation, heating and transportation purposes. While the vast majority of methane used in society today comes in the form of natural gas, there is rapidly growing interest in capturing the methane formed from decaying biomass. This, of course, does not mean capturing the methane released from all the natural sources in nature. It means setting up dedicated biogas facilities where the biogas process can be fully contained, controlled and optimised and a commercially viable industry can be established, harnessing nature's potential to produce renewable, environmentally sustainable, gaseous biofuel.

Biogas has been used in household and farm-scale applications for many years. Biogas (or sewage gas) production has been a standard process since the 1930s for the stabilisation of sewage sludge. What has changed over the last 40 years or so is that biogas production has been achieved on a more industrial scale, with a higher efficiency, degree of complexity and specification, particularly in Europe and in North America. Since the start of the twenty first century, policy makers have recognised the fact the biogas production can answer a number of challenges simultaneously. It can reduce emissions of greenhouse gases (GHGs) such as methane (for example from slurry storage), it can provide a renewable source of energy (for renewable electricity, heat or transport) and it can lead to reduced impacts of pollution by waste disposal. Equally important, the process upgrades the waste into a product and makes it a valuable organic fertiliser, thus closing the cycle from soil to crop, to product, to waste and back to the soil. This recognition has led to rapid growth of the biogas sector over the last two decades, which has been promoted through legislation with various targets set worldwide for renewable energy and reduced GHG emissions.

The biogas handbook is targeted at a range of readers. It aims to provide

detailed information on the whole biogas process chain and thereby to be a sound basis for readers with at least a basic understanding of science or engineering who want to become knowledgeable in the field of biogas. The level is aimed at degree and masters level students, project planners, policy makers and regulators. As a handbook, it contains a breadth and depth of knowledge on biogas processes but can also be considered as a starting point in a detailed study or project and a point of access to a wide range of further expert sources of information. Many references are given for further reading for those needing to go deeper into a particular subject. The individual chapters have been written by the best known experts in the respective fields.

The book considers all aspects in the chain from the origin of the biomass feedstocks, feedstock selection and preparation, the anaerobic digestion process, biogas plant equipment design and operation, through to utilisation of the biogas for energy production and the residue, the digestate, which can be used as a biofertiliser. Biogas utilisation is addressed with respect to combined heat and power and upgrading to natural gas equivalent biomethane for transport applications and injection into the natural gas grid. The book also addresses environmental impacts and commercial market applications such as trading of green certificates.

The editors are indebted to members of the International Energy Agency, Bioenergy Implementing Agreement, Task 37 (Energy from Biogas) and to other experts in the biogas field who have contributed to the 19 chapters of this handbook. Their dedication is thankfully acknowledged.

The editors are convinced that the biogas sector will continue to grow and make its contribution to renewable energy generation and reducing negative impacts on the environment, both in the form of GHG emissions and the pollution of soil and water courses. Biogas technologies will doubtless continue to expand for the treatment of biodegradable waste. There are also well accepted opportunities for growth in the use of purpose-grown crops for biogas production where substantially better energy yield is achievable than for the production of liquid biofuels from the same crops. Finally, emerging research is showing the potential for biogas and/or biomethane to contribute to meeting energy demand from grids that are increasingly supplied by strongly fluctuating inputs from wind or solar.

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Jerry Murphy, Cork, Ireland

Organisations supporting IEA Bioenergy

Task 37 – Energy from Biogas

Austria

Austrian Federal Ministry for Transport,
Innovation and Technology

IEA RESEARCH
COOPERATION

bm vrt

Denmark

Energiteknologisk Udvikling og
Demonstration (UDEP)



Biogas Advisory and Consulting
(Biosantech)



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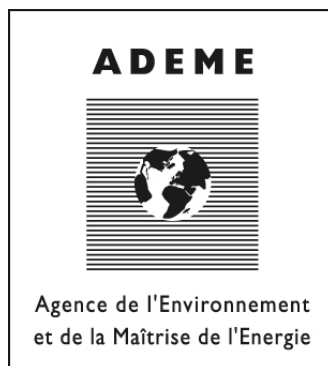
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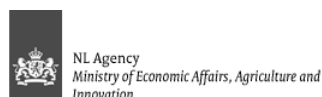
Sweden

Swedish Energy Agency



The Netherlands

NL Agency: Ministry of Economic
Affairs, Agriculture and Innovation



Biogas as an energy option: an overview

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Abstract: This chapter describes the potential, requirements, risks, required general conditions and the prospects of biogas production. The necessity of effective government support is emphasized. The pressing question of the ecological importance of biogas production is discussed and it is made clear that state-of-the-art biogas plants are no risk either to humans or the environment. One conclusion at which the author arrives is that biogas has a special role to play in the scenario of the fundamental change of today's energy supply patterns because electricity and heat can be produced as and when needed.

Key words: biofuel, biogas, biomass, biomethane, electricity, energy balance, fixed-price support system, transport biofuel, life cycle assessment.

1.1 Introduction

Biogas is produced in biogas plants by the bacterial degradation of biomass under anaerobic conditions. There are three categories of biomass: (1) substrate of farm origin such as liquid manure, feed waste, harvest waste and energy crops; (2) waste from private households and municipalities such as separately collected organic waste (in organic waste containers), market waste, expired food or food waste; (3) industrial by-products such as glycerine, by-products of food processing or waste from fat separators. The organic substance is converted to biogas by bacteria in several steps in airtight digesters. The bacteria are similar to those found in the pre-stomachs of ruminants.

As with fossil natural gas, the main component of biogas that determines the energy content of the gas is flammable methane (CH₄). Depending on

the substrate digested in the biogas plant, the methane content of the biogas fluctuates between 50% and 75%. The second main component of biogas is carbon dioxide (CO_2) with a share between 25% and 50%. Other components of biogas are water (H_2O), oxygen (O_2) and traces of sulfur (S_2) and hydrogen sulfide (H_2S). If biogas is upgraded to biomethane with approximately 98% methane in a biogas treatment plant, the biomethane has the same properties as natural gas.

After simple desulfurization and drying, biogas can be converted to electricity and heat in cogeneration units (combined heat and power (CHP)) or the biogas is burnt to produce heat. After treatment to natural gas grade, the so-called biomethane can be used in all applications commonly known for natural gas. Thus, biogas and biomethane produced from biogas are flexible renewable fuels that can be stored. Motor fuel, electricity and heat can be produced from them, which makes them important functions in the context of sustainable energy supply. Besides, biogas can also replace carbon compounds in plastic products.

Experts are not agreed as far as the importance of biogas for the sustainable supply of energy is concerned. Basically, a difference should be made between two different origins of the substrate on which biogas plants feed: waste and energy plants. Whereas the untapped reserve of digestible organic waste is enormous on a world scale, large unused areas of land on which energy crops can be cultivated are also available. For Europe, including the European succession states of the Soviet Union, it has been calculated (Thrän *et al.* 2007) that by the year 2020, 250 billion standard cubic meters (m^3_{N}) of biomethane from digested feedstock could be produced, which would be enough to meet 50% of the present gas consumption in the 28 European Union (EU) member states. These figures illustrate that biogas can make a sizable contribution to the energy supply. Besides, biogas is a versatile fuel: biogas produced from substrates by digestion, is the only renewable fuel at present that is a viable alternative to fossil natural gas and can be used for all purposes for which natural gas is used and also by the same infrastructure. Thus, biogas technology can contribute to solving the pressing questions of safe and sustainable energy supply for electricity, heat and transport fuel.

1.2 Biogas technologies and environmental efficiency

Biogas is produced by anaerobic bacteria that degrade organic material to biogas in four steps: hydrolysis, acidification, production of acetic acid and production of methane. The product of the digestive process, raw biogas, consists of 50–75% methane, 25–50% carbon dioxide and 2–8% other gases such as nitrogen, oxygen and trace gases (e.g. hydrogen sulfide (H_2S), ammonia (NH_3) and hydrogen). Before the biogas can be converted into

electricity in engines at the place at which it is produced, the raw biogas must be cleaned in a first process in which the water vapor saturated biogas is desulfurized and dried by cooling.

Certain basic conditions must be met to enable the bacteria to degrade the substrate efficiently. These are: (1) absence of air (anaerobic atmosphere); (2) uniform temperature; (3) optimum nutrient supply; (4) optimum and uniform pH. The equipment of a biogas plant should be able to meet these basic requirements. Therefore, a biogas plant designer should know from the beginning what kind of substrate the plant will feed on so that the right equipment for efficient biogas production can be selected.

The methods of biogas production can be characterized by the number of process steps, the process temperature, the dry matter content and the way in which the substrate is fed. Biogas plants feeding on agricultural by-products such as liquid manure, harvest residue and energy crops often employ a single-step process in the mesophilic (32–42°C) temperature range with wet fermentation and quasi-continuous feeding. The method can be varied depending on the requirements the process must meet in terms of speed, the degree of digestion and the hygienizing action. For example, hydrolysis as the first step usually accelerates the process and may also result in a higher degree of degradation. Increasing the process temperature from the mesophilic (32–42°C) to the thermophilic (45–57°C) level also speeds up degradation and improves the health status of the substrate (Eder and Schulz 2006).

Better health results are also reported for the plug flow fermentation method in which the substrate is mixed by the slow rotation of an agitator and moved through a long horizontal digester. Because the substrate in the digester is not mixed in one pass, quick passage from the feed point to the delivery point is prevented and a minimum dwell time of the substrate in the digester is obtained. This enforced dwell time of the substrates improves the hygienizing action of this method. Unlike the full-mix wet digestion process, a plug flow digester can normally carry a higher volume load of organic material per cubic meter of digester volume.

If the substrate digested in the biogas plant contains more than 20% dry matter, so-called dry digestion methods will normally be applied. In these methods, the digester is charged with stackable substrates. The substrates are not mixed, but a liquid called percolate runs through them. After a sufficiently long dwell time, the digester is opened and the digested product removed. In addition to this batch process, several other methods for digesting solid substrates have been developed that like the batch processes, are now primarily used for digesting municipal waste. The different processes will be dealt with in another chapter of this handbook and so are not described in detail here.

The purpose of biogas technology is the conversion of organic substances

to methane as fuel and valuable fertilizer from available resources that otherwise would go unused. This is particularly the case when exclusively by-products and waste are used as substrates for digestion. But even if energy crops serve as the substrate for biogas production, the energy balance is positive as Effenberger *et al.* (2010) were able to demonstrate with scientific support from the example of ten biogas plants.

In addition to the energy balance, the carbon balance is an important indicator assessing the environmental efficiency of a technology providing electricity from renewable sources. The carbon footprint of a biogas life cycle assessment should consider the carbon dioxide equivalents for the construction and operation of the biogas plant, the feedstock, the uncontrolled methane emissions from the plant and the digested residue, and during spreading in the field. Methane emissions that may have been avoided by the digestion of liquid manure, the emission of carbon dioxide prevented by the use of the fertilizer and the credits for the supply of electricity and heat improve the energy balance further. It goes without saying that in calculating the footprint it is assumed that the generally accepted rules of technology are observed along the entire production chain (Bachmaier *et al.* 2009).

As methane has a 25 times higher impact on climate than carbon dioxide (IPCC 2007), the causes of the uncontrolled release of methane in the process of biogas production and utilization should receive particular attention. These are, in a biogas plant, leaks from the digester, the gas piping or the digestion residue store, as well as methane slip due to incomplete combustion of biogas in the engine. Leaks are relatively easy to detect by regular leak checks. Avoiding leaks also improves the financial return of the process because emitted methane bears on the earnings situation of the plant. The so-called methane slip is a function of the cogeneration unit. Suppliers of cogeneration units are required to disclose relevant data and every buyer should be aware of the methane slip performance of the engine and insist that the slip is warranted. If an engine fails to meet the specified methane slip prescribed in the country in which the engine operates, lean gas combustion equipment may have to be installed to ensure methane is not allowed to escape into the atmosphere. The ecobalance of a biogas plant should also consider storage and the spreading of the digested material in the fields. The best approach is to ensure that as much methane as possible is released by digestion so that very little methane will be set free if the digested material is stored without cover. As an alternative solution, the digestate can be provided with a gastight cover. This is the preferred solution when it cannot be ensured that the digestion residue contains little methane. This is particularly the case when the flow of material from digestion is irregular and the bacterial populations are required to adapt to different substrate frequently.

When the biogas process feeds on an energy crop substrate, the energy input and possible emissions of nitrous oxide (N_2O) from the soil must be considered. At present, there are no uniform standards for reliable comparisons. Despite that, however, assumptions of possible N_2O emissions in connection with the cultivation of energy plants are included in the life cycle assessment.

In the traditional process of biogas production in Europe today, energy yields in the form of electricity and heat must also be included in the positive side of the life cycle assessment. As a rule, the average CO_2 emission of the power mix in a country serves as benchmark. Deducted from this is the CO_2 equivalent released in the production of biogas-based electricity and the bottom line then indicates the amount of CO_2 release avoided by the electricity from biogas.

The same procedure is applied when calculating credits for the use of heat from cogeneration. As a result, a biogas plant in which the biogas is converted to electricity and much of the heat coproduced can be used distinctly improves the life cycle assessment of that plant. For this reason, biogas plants operating in cogeneration mode and achieving a high degree of heat utilization have a better life cycle assessment than biogas plants where the gas is only converted to heat or plants whose gas is upgraded to biomethane as fuel (Bachmaier *et al.* 2009). A similar analysis may be undertaken for the use of biomethane as a transport fuel with petrol or diesel as the displaced fuel (Korres *et al.* 2010).

A positive life cycle assessment is a priority target of any biogas plant. The relatively high level of inputs required for the production of biogas, plus the conversion of the gas into electricity, heat or transport fuel can only be justified if this form of producing renewable energy also contributes to reducing emissions of harmful climate gases. As regards biogas, it should be noted, in addition, that biogas is the only versatile energy source and at present the only available gas from renewable sources; renewable hydrogen infrastructure is not widely in place and the technologies are not yet commercially available. Another point in favor of biogas is that – irrespective of whether it is converted into electricity at the place where it is produced or at the end of the gas network – electricity and heat obtained from it are available to meet demand. In this way, biogas can compensate other fluctuating renewable power sources and thereby fill an important function in the energy supply of the future. Thus, a life cycle assessment alone cannot determine whether the production of biogas is viable economically, but biogas should be considered as part of the whole system of sustainable energy supply.

1.3 Political drivers and legislation

Energy markets, considered on a global scale, very rarely follow the rules of a free market economy. The reason for this is that the price of energy in the market is not determined by demand and supply alone but, in addition, is subject to a multitude of political and government regulations. These regulations follow the core requirements of economy, ecology and security of supply and differ in the different weightings they give to these three requirements. Besides, monopolistic or at least oligopolistic market structures, in which the market is dominated by a few energy suppliers, are often found in the energy industry. For the most part, electricity and natural gas are distributed through lines and networks that until not so long ago belonged to the energy supply companies. Although, under current European legislation, network operators and energy suppliers were 'unbundled', the system had been averse to any structural change in the energy sector for many years. Today, however, network operators and energy suppliers in Europe are formally separated from each other, and consumers find it much easier to opt for another supplier.

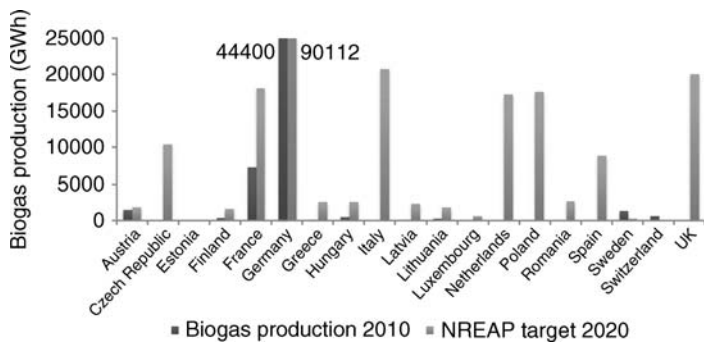
Another typical feature of the energy markets is that the emission of greenhouse gases due to the production of energy – a major cost factor of the economy of any country – is not reflected in the pricing policies in the energy markets. One attempt at integrating the external cost of energy provision in the prices is the trade in 'pollution rights' in the form of CO₂ certificates. This tool has not been working well on a global scale because there is no political will of helping a genuine market into being at the international level.

If the provision and utilization of renewable energy is a target of energy policy, the required mechanisms that cause potential actors to supply renewable energies must be adopted. In other words, demand for energy that is more expensive but 'cleaner' than energy from conventional sources must be generated. In this process, the quantitative and qualitative potentials of the different sources of renewable energy must be considered if the targets of using renewable energy are, in fact, to be attained. It will not do, for example, to subsidize the most cost-effective renewable energies with low resources and not to use the more expensive ones with large resources as this may prevent the quantitative target to be met and power will not be available when it is needed. Therefore, the urgent need is for a mechanism that, while making fullest use of the available quantity potential, also takes care that electricity, heat and transport fuel are supplied in accordance with demand. So far, no mechanism that would meet all these requirements is known. The EU has defined the target to reduce, by 2050, greenhouse gas emissions by 85–90% from the level released in 1990. The share that renewable energies will have in the reduction of greenhouse gas emissions

has not yet been defined by the EU (European Commission 2011). Milestone targets in the EU’s roadmap defined so far are 30% renewable energies in total energy consumption and 45% given by the renewable energy industry associations (EREF 2011). Discussion about the share of renewable energies in the final consumption of energy cannot be reproduced here. It is clear, however, that the sharing of markets and profits from the future energy supply system is lurking behind this discussion and that is why the debate has become so heated. Very different actors are meeting in this arena: on the one hand, the conventional energy industry with typical large industry structures and, on the other, small- and medium-size firms offering and operating plants and equipment for the supply of renewable energies.

An overview of the current state of biogas utilization and the targets of the different European countries based on National Renewable Energy Action Plans (NREAPs) is contained in *Biogas Report 2011* published by the European Biogas Association (EBA 2011). It can be seen from these plans that some countries have a considerable amount of catching up to do to meet the level of biogas use in other countries (Fig.1.1). Overall, the production of electricity from biogas is set to increase from 25.2 terawatt-hours (TWh) in 2009 to 63.3 TWh by 2020. Countries such as Germany, Sweden and Austria, with a high number of biogas plants today, will probably meet these goals. Considerable progress has also been made in Italy and the Czech Republic, whereas countries such as Poland and the Baltic states will probably have to reconsider their support policies for biogas (Fig.1.1).

The search for state-aid instruments that would help increase the present share of renewable energies in the energy supply system is a worldwide process. The target is to create conditions for potential owners of plants for the provision of renewable energy that enable them to connect their plants to the available energy distribution networks and market their products at



1.1 Biogas production in 2010 and targets based on National Renewable Energy Action Plans (NREAPs) (source: EBA 2011).

cost-covering prices. Governments can enact legislation to give priority to the connection of plants for renewable energies to the energy grids. Such regulations are necessary because the actors involved in the conventional energy industry are not normally interested in stepping back in favor of other suppliers. Two instruments have been applied to ensure that higher prices are obtained for renewable energy: quota systems and fixed-price systems (feed-in tariffs).

Under quota systems, a target is set for renewable energies and fines threaten for those failing to meet the quota. The fact that the energy supplied is from renewable sources is usually demonstrated by a certificate, which can also be traded without direct relation to the energy. In practice, quota-based models have not been effective so far because there are no reliable general economic conditions on which plant owners can rely as regards a minimum level of security of their investment. As a result of the lack of planning certainty, only investors with sufficient capital enter the market and expect an appropriate return on their planning uncertainty. According to experience in the UK, the prices of energy funded in this way are higher by one third in comparison with fixed-price systems. Quota models normally also contain rules as to whether the renewable energy should be wind, solar, biomass or hydropower. As a result, only the most cost-effective renewable energies are used and their quality is poor because in many cases the lower-priced renewable energies cannot be supplied continuously. Another negative effect of the quota models is the fact that, as a result of the absence of investment certainty, efficiency improvements in the supply of energy can hardly be expected because of the absence of incentives for industry to invest in longer-term research and the low level of competition among the few players in the market. Due to the small number of actors, profits from windfall gains have been achieved under the quota system (AEE 2010).

Under fixed-rate models, typically, fixed rates are paid for the feeding in of different renewable energies for a certain term after start-up of the production plant. The higher cost in comparison with conventional electricity is then split among all electricity customers. This gives plant owners the reassurance that their investment is certain and even local actors can obtain loans from banks for funding projects. Companies supplying equipment for the production of renewable energies can invest in research and development because they also know that their capital investment is protected. Technological progress in the different industries is encouraged in an optimum way. The big challenge, however, is that the feed-in rates paid must be verified regularly. They must be sufficient to enable plant owners to fund investments and make equipment suppliers confident of their investment in research for higher efficiency. On the other hand, the feed-in tariffs must not be so high so that no windfall gains result for plant

suppliers and owners which, in the final analysis, must be paid by the general public. An exhaustive analysis of fixed-price models is given by Mendoça *et al.* (2010).

One of the first countries to introduce the fixed-price model was Germany. Here, the Renewable Energies Act (EEG) went into effect in the year 2000. It proved to be the starting point for growth in all renewable energy sectors and the number of biogas plants increased considerably. The EEG was revised in 2004, 2009 and 2012. The feed-in rates were changed and certain plant constellations subsidized. Probably the most important change as far as biogas is concerned was the adoption of a bonus for feeding electricity from renewable sources. With this bonus, energy crops were cultivated for the production of biogas and biogas crop production established itself as a sector in its own right in agriculture. Along with this development, many farm by-products that otherwise would have been spread onto fields without utilization of the energy they contain provided substrates for biogas production. In fact, about 10% of the liquid manure produced in Germany already goes to biogas plants.

Other by-products such as feed waste, harvest residue and agricultural products that cannot be marketed as food because of low quality are ideal feedstock for biogas plants. According to calculations by the German Biogas Association (GBA 2011), approximately 26.5 TWh of electricity per year could be produced in Germany if all digestible agricultural by-products and wastes were converted to biogas. This would be enough to supply 7.5 million three-person households with 3500 KWh of electric power per year.

The possibility of using very different substrates in biogas plants makes biogas a particularly interesting source of renewable energy. However, this also makes the design of a successful support framework much more complicated than in the case of other renewable energy sources. There is not only a wide variety of feedstocks, but there are also as many potential utilizations of the product: transport fuel, heat only, or combined electricity and heat. Furthermore, there is the question of whether the gas network infrastructure should be used for biogas as well. If it should, the support regulations must be defined accordingly. Before a decision on a support instrument and its structure is taken, the direction in which the biogas sector is to be heading must be clear. Looking at high energy efficiency, it seems logical to place one focus of support on the production of electric power and heat in cogeneration units. As biogas and also heat can be stored, cogeneration systems that can supply both electricity and heat as and when needed should receive particular support. Another focal support to consider is biomethane as fuel because, among the biofuels, it has the highest energy efficiency (Smyth *et al.* 2009). Basically possible, but not advantageous for efficiency reasons, is the use of biogas or biomethane for

the production of heat by burning the gas. This use would only be reasonable in the long term if the heat is produced by a gas flame such as in some industrial applications, (e.g. in the glass industry).

Considering the necessity of converting the whole energy supply system and particularly electricity supply to renewable sources, a main use of biogas and other renewable gases in the future will be as a source of electric power at times when other fluctuating renewable energies such as wind or solar are not available. The available support mechanisms should thus encourage meeting the demand by renewable electric power. At present, biogas, in addition to hydroelectric power, is the only renewable energy source that – given the present state of technology – can supply electric power as and when needed. In this respect, biogas is a service – and a cost-covering price must be paid for this service because otherwise it will not be delivered.

In connection with the available gas network, biogas upgraded to biomethane can deliver this system service well and at short notice because the gas network, as a rule, has extensive storage capacity. Sterner (2009) has shown, using the example of Germany, that the storage capacity available in the gas network is 1000 times larger than that of all available pumped-storage power plants together. With this in mind, the biogas industry can offer ready solutions in today's international quest for storage possibilities and the supply of electric power to meet the demand from renewable sources. The technology of treating and feeding biomethane available today is a direct and immediately available solution. In the long term, the combination of biogas upgrading plants in which carbon dioxide is eliminated from the biogas with plants converting excess electricity into gas (as described by the Sabatier equation) can offer an additional way out. In these plants, hydrogen is at first produced by electrolysis and then carbon dioxide is added to obtain methane (power-to-gas). This is a promising method of combining the finite biomass resource with the enormous potential of wind energy in an efficient way (Sterner 2009).

Today, no ready answer can be given to the question of what is the ideal support mechanism that would enable making the most cost-effective and efficient use of biogas as a versatile source of source energy. In view of the key role played by biogas produced by the digestion of biomass, despite the limited availability of the resource, it is important to ensure continuous development of the biogas sector through a continuous and clear-cut support policy. There is no other way in which the industry, by research and development, can face the challenges for higher efficiency and integration in energy supply systems of the future.

1.4 Health, safety and risk assessment

Biogas plants are technical facilities that process products and by-products from farming and food processing, different types of organic waste and energy crops. Digestion produces biogas and a digested product that, in most cases, provides a valuable input as fertilizer. Biogas is flammable but not explosive; an explosive environment can develop, however, if methane is present at very low concentrations of 6–12%.

All mechanical and moving parts of the biogas plant can pose hazards and the uncontrolled escape of biogas or fermentation products is another potential hazard source. The applicable regulations for device and product safety as well as health and safety must be observed during the construction and operation of a biogas plant. Depending on the size, type and environment of the plant, different countries have established sets of rules for the technical safety of plants which, at least in part, are prescribed by European directives. Biogas plants built primarily for the treatment of organic waste from industrial processes or households are subject to the regulations in effect for industrial waste treatment plants. Plants processing digested sludge from waste water treatment plants come under the waste water treatment regulations. Many biogas plants on farms are covered by rules applying to agriculture or new regulations are enacted specifically for such plants.

The target for every biogas plant must be to ensure the highest possible level of safety for humans and the environment. It is important that safety regulations can be understood by those who are expected to observe them and that they can be applied in the applicable economic framework. In light of this, the rules for industrial waste treatment plants can and must be different from those applying to the construction and operation of biogas plants on farms that process primarily manure and renewable primary products.

Experience in Germany, where altogether about 7000 biogas plants were in operation in 2011, most of them in a farming context, has shown that most accidents were due to mistakes on the part of operators. In many cases, the accident was caused by deflagration or explosion of escaping biogas. Rarely was an accident due to the toxic action of hydrogen sulfide present in untreated biogas or in the feeding area of the biogas plant. There was hardly a case in which the technical rules for the construction of biogas plants had not been sufficient or had not been observed – it was rather a question of wrong handling. The operators of biogas plants must therefore be trained thoroughly. Another German experience is that fewer accidents happen during normal operation than happen during construction, start-up or maintenance of a biogas plant. Again, personnel doing the work must be trained and made aware of the risks involved.

In addition to the hazards that can occur in connection with the mechanical operation of biogas plants or the uncontrolled escape of biogas, the risk that pathogenic germs may spread with the digestion residue in fields is a topic often discussed by the general public. Because the substrates in biogas plants can contain bacteria, viruses and parasites that may cause disease in man, animals or plants, this fear is not at all unfounded at first sight. Generally, the digestion process has an impact on the health risks of a substrate. Different scientific studies have shown that germs in a substrate are reduced by digestion in a biogas plant (Bagge *et al.* 2010, Lebuhn *et al.* 2007). Hence, when a substrate is digested that normally would have served as organic fertilizer without any further treatment, the biogas process generally reduces the risk of pathogenic germs. If a biogas plant processes waste that contains an additional health risk, the additional conditions that must be met before the digestate can be returned to the fields should be considered. For example, if animal by-products are processed, European Regulation 1069/2009 stipulates health rules as regards animal by-products not intended for human consumption (European Commission 2009). The regulation defines three categories of substrate with different risk levels, specifies substrates that may be spread and those that must not, and also spells out the health measures to be taken when the digested product is to be used as fertilizer.

Factors affecting the health status of the substrate include temperature, retention time, pH and ammonia content (Eder and Schulz 2006). These parameters are defined by the texture of the substrate, the method of digestion and a hygienization unit that may be installed. At the European level, the requirements on biowaste treatment are laid down in the EU Waste Framework Directive (European Commission 2008) and Regulation 1069/2009. Concrete actions are defined in national ordinances regarding the treatment of biological waste but also the use of organic fertilizer. Regulation 1069/2009 requires that category 3 material should be treated at 70°C for 1 hour. Category 3 materials include, for example, food remains, kitchen and canteen waste, content of fat separators and flotage.

In addition to treatment in a hygienization unit connected upstream of the biogas plant, thermophilic digestion at 55°C and at least 24 hours dwell in the digester achieve the equivalent of 70°C for 1 hour. In that case, however, the process owner must demonstrate that the health effect is not impaired by short-circuits in the flow. In addition to the possible transmission of disease to humans or animals, the use of organic digestate as a fertilizer also raises the question of how far weed seed can be spread. In this respect, Schrade *et al.* (2003) were able to show that all weed seeds examined were not germinable after thermophilic digestion and most seeds had lost their germination capacity after 24 hours under mesophilic (35°C) conditions and

the most resistant seeds, such as tomato and sorrel, had lost this capacity after a dwell period of three weeks.

In conclusion, it can be stated that biogas plants do not involve a high safety risk for man or nature if the applicable provisions are observed and the construction and operation of the plants are state-of-the-art. Despite daily routine handling of a biogas plant, plant operators should always observe the latest safety standards and applicable rules of conduct. In this way, people working at biogas plants can be confident that their safety and health are protected in the best possible way. Under normal operating conditions, biogas plants present no hazard for the environment. No doubt, a storage tank – if handled improperly – could be damaged, a pipeline could burst, or gas or digestion substrate or product could spill and cause environmental damage. However, such damage can be minimized when all applicable conditions are met, requirements observed, the plant is state-of-the-art and the operators are regularly trained.

1.5 Conclusions and future trends

Biogas is a versatile renewable source of energy produced by anaerobic digestion of different substrates. Due to the very wide range of input materials, a significant amount of energy can be produced with biogas. Thrän *et al.* (2007) estimated that 28 EU and the European succession states of the former Soviet Union could produce 250 billion standard cubic meters of biomethane from digestion in biogas plants by 2020. According to data from the study of Thrän *et al.* this figure could double if biomethane from the thermochemical production of synthetic natural gas is added. In total, 500 billion standard cubic meters of biomethane would be enough to meet the present natural gas consumption of the 28 EU member states. Even if it will probably not be possible to produce the potential biomethane volume forecast by the study, it is very clear that the biomethane potential available at European level can make a sizable contribution to the energy supply of the future.

In addition to the sheer volume, the quality of biogas as energy source is of extreme significance. Untreated biogas can be converted into electricity and heat by cogeneration at the place where which the gas is produced: the heat can be used locally and the electricity fed into the public grid. This is the preferred way in which the energy is used in Europe at present. Electricity produced by cogeneration is available at any time and can supply base load demand, but could also be generated to meet increased demand if sufficiently large gas storage capacity were available. With raw biogas upgraded to natural gas level, it can be fed into the available gas network and, in that case, the infrastructure of the gas network would allow the use of biomethane for any purpose for which natural gas is used. The two most

important characteristics that make biomethane in the gas network so attractive is that the gas is transported to the place where the end product is needed and it can be stored. As gas, biomethane is conveyed to where the heat from cogeneration is also needed. This means another substantial improvement in biogas efficiency. In the future, the storage capacities of the available natural gas infrastructure will attain particular importance because they can hold very large volumes of biogas/biomethane from which electric power and heat can be produced where and when needed. Even if – unlike wind and photovoltaics – the production of biogas is limited and the cost of electricity from biogas today is clearly higher than the cost of wind power and (on an equivalent level) solar electricity, the fact that biomethane can be stored will secure an important function for that gas in future power supply systems. Besides, biomethane could also be used as fuel for powering vehicles available in the market today.

Due to its variable uses, storability and high energy efficiency, biomethane will perform an important function in a future sustainable power supply system. How fast and at what cost this function can be performed depends largely on the general political and legal conditions. These should enable suppliers of biogas technology to proceed with research and development to make biogas technology fit for the challenges of the future. It will also be necessary to press ahead with positive public relations to improve the public acceptance of biogas plants. It can already be seen that wherever several biogas plants are constructed, action groups against them are formed. The biogas industry and governments must focus on communication of the positive role of biogas in a future sustainable power supply system.

1.6 Sources of further information and advice

Biogas can do it (Biogas kann's), Information booklet with answers to FAQs around biogas, www.biogas-kanns.de

Biogas Forum Bayern, www.biogas-forum-bayern.de

European Biogas Association (EBA), www.european-biogas.eu

European Renewable Energy Council (EREC), www.erec.org/

European Renewable Energy Federation (EREF), www.eref-europe.org/

German Biogas Association (GBA), Fachverband Biogas e.V., www.biogas.org

German Federal Environment Agency (Umwelt Bundesamt UBA), www.umweltbundesamt.de/energie-e/index.htm

German Renewable Energy Agency, Agentur für erneuerbare Energien (AEE), www.unendlich-viel-energie.de/en/homepage.html

IEA Bioenergy Task 37, <http://www.iea-biogas.net/>

Information portal on renewable energies in Germany and Europe, German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

(BMU), www.erneuerbare-energien.de/inhalt/48192/4590/www.erneuerbare-energien.de
 Price report, www.eref-europe.org/index.php/what-we-do/price-report
 RES LEGAL, Legislation on renewable energy generation, www.res-legal.de/index.php?id=1&L=1

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Biomass resources for biogas production

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Abstract: Biomass resources for biogas, also referred to as anaerobic digestion feedstock or biogas feedstock, include various categories of organic materials. This chapter highlights the main characteristics of biogas feedstocks including their suitability, availability, digestibility and purity. Although the feedstock for biogas can be categorized according to various criteria, this chapter groups them according to their sectors of origin (agricultural, industrial, municipal and aquatic), highlighting the merits and limitations of the most utilized feedstock types within each category. The basics of feedstock availability, supply and logistics and their influence on issues related to biogas plant location are also emphasized.

Key words: biomass for anaerobic digestion (AD), AD feedstock, biogas feedstock, organic wastes, digestible biomass.

2.1 Introduction

Biomass is the general term used to describe all biologically produced matter and therefore includes all kinds of materials and substances derived from living organisms. Biomass is widely used for energy purposes and supplies today some 50 EJ globally, which represents about 10% of the global annual primary energy consumption (World Energy Council, 2010). According to the World Energy Council, there is still significant potential to expand biomass for energy use, including for biogas production, by tapping the large volumes of unused residues and wastes. Biomass originating from

forestry and agriculture, along with industrial and municipal residues and wastes, are the biomass types used as feedstock for energy generation. Biomass resources suitable as biogas feedstocks, usually named anaerobic digestion (AD) feedstock are represented by a large variety of organic materials available on a renewable basis, ranging from simple compounds to complex high-solid matters. They usually have a high content of sugar, starch, proteins or fats, and a common feature is their ability to be easily decomposed through AD.

2.2 Categories of biomass appropriate as feedstocks for biogas production

Historically, AD has been associated with the treatment of animal manure and slurries and with stabilization treatment of sewage sludge from wastewater plants. During the 1970s, organic wastes from industry and municipal wastes were introduced as biogas feedstocks. This was due to increasing environmental awareness and demand for adequate waste management strategies and was possible because of the development of high-rate reactor configurations and sophisticated process control techniques (Steffen *et al.*, 1998). The cultivation of crops such as maize, grasses, cereals, beets, potatoes and sunflowers, specially dedicated to be used as feedstock for biogas, was developed in the 1990s in countries like Germany and Austria, although the idea is much older – the methane potential of various crops was investigated in the 1930s by Buswell (Murphy *et al.*, 2011).

The biomass resources amenable to biogas production can be grouped into categories according to various criteria. According to the taxonomic rank (Latin *regnum*) of their origin, they can be vegetal (*plantae*) and animal (*animalia*). According to the sector generating them, they can be agricultural (animal manures and slurries, vegetable by-products and residues, energy crops), industrial (organic wastes, by-products and residues from agro-industries, food industries, fodder and brewery industries, organic-loaded wastewaters and sludges from industrial processes, organic by-products from biofuel production and biorefineries, etc.), municipal (source-separated household waste, sewage sludge, municipal solid waste and food residues). Across these sectors, wastes, residues and by-products of different biomass value chains are the most sustainable materials now used as AD feedstocks (Table 2.1).

Over the last decade, the potential of aquatic biomass as a feedstock for biogas has received increasing attention and has become the focus of research efforts around the world in attempts to develop cost sustainable and technically feasible full-scale applications for the culture, harvesting and

Table 2.1 Characteristics of some biogas feedstocks (* indicates methane booster)

Type of feedstock	Organic content	C:N ratio	DM ^a (%)	VS ^b % of DM	VS (%)	Methane yield (m ³ CH ₄ /kg VS)	Methane production (m ³ CH ₄ /m ³)
Animal wastes and by-products							
Pig slurry	Carbohydrates, proteins, lipids	7	5	80.0	4.0	0.30	12.0
Pig manure, solid	Carbohydrates, proteins, lipids		20	80.0	16.0	0.30	48.0
Cattle slurry	Carbohydrates, proteins, lipids	13	8	80.0	6.4	0.20	12.8
Cattle manure, solid	Carbohydrates, proteins, lipids		20	80.0	16.0	0.2	32.0
Poultry droppings	Carbohydrates, proteins, lipids	7	5	80.0	4.0	0.30	12.6
Poultry manure, solid	Carbohydrates, proteins, lipids		20	80.0	16.0	0.30	48.0
Stomach/intestine content, cattle	Carbohydrates, proteins, lipids	4	12	80	9.6	0.40	38.4
Stomach/intestinal content, pig	Carbohydrates, proteins, lipids	4	12	80	9.6	0.46	44.2
Plant wastes and by-products							
Straw	Carbohydrates, lipids	90	70–90	80–90		0.15–0.35	
Garden wastes	Carbohydrates, lipids	125	60–70	90		0.20–0.50	
Grass	Carbohydrates, lipids	18	20–25	90		0.30–55	
Fruit wastes	Carbohydrates, lipids	35	15–20	75		0.25–0.50	
Organic wastes from industries							
Whey	75–80% lactose, 20–25% protein	—	5	90	4.5	0.33	15.0
Concentrated whey	75–80% lactose, 20–25% protein	—	10	90	9.0	0.54	31.5
Flotation sludge	65–70% proteins, 30–35% lipids	—	5	80	4.0	0.54	21.6
Fermentation slop	Carbohydrates	7	1–5	90		0.35–0.78	
Whole silage (grain)			12.6	91	11.5	0.47	53.9
Thin silage (grain)			8.5	86	7.3	0.50	36.5
*Fish oil	30–50% lipids	—	90	90	81.0	0.80	648.0
*Soya oil/margarine	90% vegetable oil	—	95	90	85.5	0.80	684.0
*Alcohol	40% alcohol	—	40	95	38.0	0.40	152.0
*Bleach clay			98	40	39.2	0.8	313.6
Olive pulp		—	24	96	23	0.18	41.4
Brewers spent grains		—	20	90	18	0.33	59.4
*Glycerine							

(Continued)

Table 2.1 (Continued)

Type of feedstock	Organic content	C:N ratio	DM ^a (%)	VS ^b % of DM	VS (%)	Methane yield (m ³ CH ₄ /kg VS)	Methane production (m ³ CH ₄ /m ³)
Energy crops							
Grass silage		17	15–40	90		<0.45	
Maize silage							
Fodder beet silage							
Sewage sludge							
Waste water sludge		5		75	3.75	0.4	15.0
Conc. wastewater sludge		10		75	7.5	0.4	30.0
Food remains		10		80		0.5–0.60	

^a Dry matter.^b Volatile solids.

utilization of biogas feedstocks (Wellinger, 2009). Although its utilization as a biogas feedstock is still in the research phase, aquatic biomass is one of the biomass types with the highest potential for renewable energy production as well as various industrial applications and a possible future alternative to energy crops.

2.2.1 Agricultural biogas feedstocks

The feedstock substrates used for biogas are primarily derived from the agricultural sector, which accounts for the largest potential for biogas feedstocks (Steffen *et al.*, 1998). These feedstocks consist mainly of various residues and by-products, of which the most important are animal manures and slurries collected from farms (from cattle, pigs, poultry, etc.). Along with manure and slurry, crop residues, by-products and wastes (e.g. straw, grasses, leaves, fruits, whole plants) are also used. Over the last decade, new categories of feedstocks have been tested and are now used in AD plants; this is the case of energy crops (maize, grasses, beets, sunflowers, etc.), grown specially for biogas production.

Animal manure and slurries

Animal farming is an important part of the agricultural sector in most countries, accounting for 18% of worldwide greenhouse gas emissions (Info-Resources 2007). Most of these emissions originate from the 13 billion tons of animal manure and slurries estimated to be produced annually around

the world (Van Horn, 1995; Harkin, 1997). Past practices allowed manure to be spread without limitation on agricultural land, but now, increasingly restrictive environmental legislations in many countries require manure treatment and management technologies such as AD. Zafar (2008) acknowledged AD in the USA as 'a unique treatment solution for animal manure, able to deliver multiple benefits, including renewable energy, avoidance of water pollution, and air emissions'. Anaerobic digestion upgrades animal manure and slurries from environmentally polluting wastes to valuable resources used for the simultaneous production of biogas (as renewable fuel) and digestate (as valuable biofertilizer).

Manures and slurries from a variety of animals can be used as feedstocks for biogas production (pigs, cattle, poultry, horses, mink and many others). They are characterized by differing dry matter contents: solid farmyard manure (10–30% dry matter) or liquid slurry (below 10% dry matter). Their composition also differs according to the species of origin and the quality of the animal feed. For simplicity, the general term 'animal manure' is often used. Manure is an excellent feedstock substrate for AD; with a carbon to nitrogen (C:N) ratio of around 25:1 and rich in various nutrients necessary for the growth of anaerobic microorganisms. It has a high buffer capacity, able to stabilize the AD process in the case of a significant pH decrease inside the digester, has a natural content of anaerobic microorganisms, is highly accessible and is cheap.

Solid manure and slurries also have some limitations as a feedstock for AD. As noted earlier, animal slurries have a low dry matter content (3–5% for pig slurries and 6–9% for cattle slurries), which gives a low methane yield per unit volume of digested feedstock, ranging between 10 and 20 m³ methane per cubic meter of digested slurry (Angelidaki, 2002), and biomass transport costs are high. Both slurries and manures contain various amounts of straw and fiber particles that are high in ligno-celluloses. The lingo-cellulosic fractions are known to be recalcitrant to anaerobic decomposition and usually pass through a biogas reactor undigested, without any contribution to methane production. As such, although manures have one of the highest potentials as a feedstock for biogas, their relatively low methane yield does not provide economic sustainability in the case of mono-digestion, so they are dependent on co-digestion with co-substrates with a high methane yield. A number of emerging technologies based on chemical, mechanic, thermal or ultrasound treatments have been tested in attempts to disintegrate the recalcitrant matter in animal manure (Angelidaki and Ahring, 2000) and make it available for the anaerobic microorganisms, with the aim of enhancing the methane yield and thus the economic efficiency of manure mono-digestion.

Manure is often co-digested with other co-substrates such as easily digestible organic wastes from various agro-industries, source-separated

household waste, energy crops or sewage sludge. The high water content in slurry acts as a solvent for the co-substrates, ensuring proper stirring in the digester and homogeneity of the feedstock mixture. Compared with mono-digestion, co-digestion of manure and organic wastes results in a higher stability of the AD process. This is partly due to higher active biomass concentration inside the digester, which is considered to be more resistant to inhibitory compounds, and partly because of the presence in the wastes of inorganic matter such as clays and iron, considered to counteract the inhibitory effects of ammonia and its respective sulfide (Angelidaki, 2002).

Anaerobic digestion of animal manures and slurries is widely applied and is increasingly developing in Europe, Asia and North America, in most places not only for renewable energy purposes but also as means to protect the environment and recycle materials efficiently into farming systems (Zafar, 2008). There is a huge potential to increase the use of manures and slurries as a feedstock for biogas, considering that only a small fraction of the global production is currently digested in biogas installations. Even in countries with very developed biogas sectors like Denmark, where manure-based biogas plants are dominant, only 3–6% of the produced animal manure and slurries is supplied to biogas plants each year. The co-digestion of animal manure and suitable organic wastes is likely to increase in the years to come, concentrated in places where these feedstock substrates are available and qualitatively suitable.

Plant (crop) residues

The category of plant residues includes various vegetable agricultural by-products and harvest residues, plants and plant parts, low-quality or spoiled crops, fruits and vegetables, and spoiled feed silage. Plant residues are usually digested as co-substrates with animal manures and other feedstock types. Most of them need to be pre-treated before feeding in to a digester. Pre-treatments range from simple mechanical particle size reduction to more complicated treatments aiming at breaking the ligno-cellulosic molecules in order to facilitate the access of anaerobic microorganisms to these structures. A particle size of 1 cm (Amon and Boxberger, 1999) allows proper handling and mixing with other feedstock types and ensures good digestion.

Energy crops

The cultivation of crops specially dedicated to energy production was developed in the 1990s in countries such as Germany and Austria, although Buswell investigated the methane potential of various crops as far back as the 1930s (Murphy *et al.*, 2011). Many varieties of crops, both whole plants

Table 2.2 Methane yields of some common energy crops (plants and plant parts)

Energy crop	Methane yield (m ³ /VS)
Maize (whole crop)	205–450
Grass	298–467
Clover grass	290–390
Hemp	355–409
Sunflower	154–400
Oilseed rape	240–340
Potatoes	275–400
Sugar beet	236–381
Fodder beet	420–500
Barley	353–658
Triticale	337–555
Alfalfa	340–500
Ryegrass	390–410
Nettle	120–420
Straw	242–324
Leaves	417–453

Source: Data compilation after Murphy *et al.* (2011).

and parts of plants, have been tested and proven to be suitable as biogas feedstock. These include maize, various grasses, various cereals, beets, potatoes and sunflowers, as shown in Table 2.2.

Some newly introduced energy crops in central Europe include *Silphium perfoliatum*, *Sorghum bicolor*, *Sorghum Sudanese* and *Helianthus tuberosus*. Mixed cropping with different plant species has also been considered. Woody crops are currently not used for AD, as biomass containing a high percentage of lignin cannot be effectively decomposed by anaerobic microorganisms. Ongoing research is currently focusing on delignification pre-treatments and technologies for efficient utilization of woody biomass as feedstock for biogas production (Al Seadi *et al.*, 2008).

The use of energy crops as a feedstock for biogas implies some specific technologic steps prior to digestion: harvesting, pre-processing and storage/ensiling. Herbaceous energy crops like grass, sunflowers, maize and sugar beet are normally used fresh or as silage. Maize is the most frequently used energy crop in the majority of existing biogas plants (Murphy *et al.*, 2011); it can be harvested with ordinary combine harvesters that simultaneously harvest and chop the whole plant for subsequent ensiling. Crops for biogas can be immediately fed to the digester or stored as silage for year-round availability. Grass crops can be harvested 3–5 times per season (Fig. 2.1). Murphy *et al.* (2011) have indicated that the composition of crops and thus their suitability as AD feedstock varies with the stage of maturity. In general, cellulosic content increases with maturity, negatively affecting the



2.1 Harvesting grass crops for silage.

Table 2.3 Dry matter yield of some annual crops; trial results from Denmark, 2008–2009

Annual crop (commercial name)	Production of dry matter (t DM/ha)
Beet (Hamilton)	23.2
Maize (Amadeo)	16.3
Jerusalem artichoke (Krogerup)	11.9
Hemp (Bialobrzeskie)	10.6

Source: Adapted from Madsen and Larsen (2011).

digestibility and the methane yield of the crop. Less mature crops, however, have a higher moisture content, making storage difficult.

Sugar beet is harvested in temperate climates later than most crops, usually in January (Murphy *et al.*, 2011). Beet crops are excellent biogas feedstock, as proven by trial results obtained in Denmark in 2009, where beet provided 30–40% higher biomass yields per hectare compared with other annual crops (Table 2.3). Beet crops also have a good uptake of nutrients until late fall, reducing in this way the risk of nutrient losses to groundwater.

The cultivation of energy crops requires a high input of fertilizers, pesticides and energy for harvesting and transport. This reduces considerably the environmental sustainability of their use for biogas and for renewable energy production in general.

The cultivation of energy crops also implies a paradigm shift for the role of farmers in society, moving from food and feed producer to energy producer as well. United Nations statistics estimate that the world population could reach 10.5 billion by 2050 (Felby, 2011). With current food production technologies, this will require a threefold enlargement of the global agricultural food production area. Meanwhile, future expectations are for the agricultural sector to be able to provide food and feed, biomass for energy, enhanced biodiversity and nature preservation, environmental protection and economy, all without increasing cultivated agricultural areas to the detriment of nature reserve areas (Madsen and Larsen, 2011). Using the crop production systems that we know today, the choice of land use between food and non-food will be an equation that is hard to solve. There is therefore an obvious need to develop new crop production technologies and to generate new knowledge in these areas. Decreasing meat consumption in human diets and the replacement of primary proteins from soya and rape used in animal feed with biotechnologically produced proteins will also decrease the land used for the production of animal feed, making it available for food and/or for energy production.

2.2.2 Industrial biogas feedstock

Considerable amounts of by-products, residues and wastes are produced by industrial activities that process agricultural raw materials. These industries include food and beverage, fodder, fish processing, milk, starch, sugar, pharmaceuticals, biochemicals and cosmetics, pulp and paper, as well as slaughterhouses (see Table 2.1). Wastes from these industries are diverse and have various methane potentials, dry matter contents, structures and compositions, according to their origin. Common for most of them is that they are homogeneous, easily digestible and rich in lipids, proteins or sugars. Many industrial wastes are used as 'methane boosters', due to their extreme high methane potential. Industrial organic wastes can be treated by AD as additional feedstocks in smaller decentralized biogas plants, large co-digesting plants or at industrial production locations (e.g. organic-loaded industrial wastewaters). In the case of organic-loaded wastewaters, the aim is to reduce their organic loading and make them suitable for further disposal and to use the produced biogas for process energy.

Many industrial organic wastes are co-digested with animal manure, with subsequent use of the produced digestate as fertilizer. Co-digestion of manure and industrial wastes enhances methane production, as most types of organic wastes have methane yields much higher than animal manure, often in the range of 30–500 m³ methane per cubic meter of feedstock (Angelidaki, 2002). As noted earlier in this chapter, co-digestion of animal

Table 2.4 Animal by-products suitable as feedstock for biogas production, according to the ABPR

Examples of animal by-products suitable for AD	Required pre-treatment according to ABPR	ABPR category
Manure and digestive tract content from slaughterhouse	No pre-treatment	Category 2
Milk and colostrum	No pre-treatment	Category 2
Perished animals	Pressure sterilization	Category 2
Slaughtered animals, not intended for human consumption	Pressure sterilization	Category 3
Meat-containing wastes from foodstuff industry	Pasteurization	Category 3
Slaughterhouse wastes from animals fit for human consumption	Pasteurization	Category 3
Catering waste, except for waste from international transport (flights, trains, etc.)	In accordance with national regulation	Category 3

manure with organic wastes results in increased process stability, due to less sensitivity to inhibitors like ammonia and sulfide. Co-digestion of industrial wastes therefore has a positive effect on the economic sustainability of a biogas plant through higher methane yields, improved process stability and supplementary income from the so-called ‘gate fees’ paid by industries to the biogas plant for the AD treatment of their waste.

Animal by-products not intended for human consumption

Digestible organic wastes comprise many types of organic wastes and by-products of animal origin. The utilization, treatment and disposal of all animal by-products not intended for human consumption is regulated in Europe by Regulation 1069/2009 (EC, 2009), also known as the European Animal By-products Regulation (ABPR), which is a revised and amended version of the earlier Regulation 2002/1774/EC (EC, 2002). Among other things, the ABPR lists the categories and types of animal by-products not suitable for human consumption, that are allowed to be used as AD feedstock in EU biogas plants and stipulates the mandatory hygienic measures and the health rules for their handling, treatment and further utilization, as summarized in Table 2.4.

By-products from biorefineries and the biofuels industry

Biofuel production facilities – and, in the future, the biorefineries that are under development today – are likely to accumulate very large amounts of organic by-products, almost all suitable for AD. In grain-processing bio-

ethanol plants, all silage fractions are typically anaerobically degradable (Rosentrater *et al.*, 2006; Cassidy *et al.*, 2008; Drosch *et al.*, 2011). In sugar cane bio-ethanol plants, the cane juice silage is also a suitable substrate for AD (Callander and Barford, 1983; Cail and Barford, 1985; Russo *et al.*, 1985), whereas the bagasse is mainly incinerated for energy recovery. In biodiesel production, the glycerol (Siles *et al.*, 2009) as well as the wastewaters (Siles *et al.*, 2010) are suitable substrates for AD, while the residual cake after oil extraction is often used as animal feed. As the biofuels and biorefinery industries become more prominent, there will be a greater need for integrating industrial AD processes.

These large quantities will demand proper strategies for the use and treatment of the anaerobic digester effluent (Fuchs and Drosch, 2011). The rising importance of utilizing by-products from the biofuel industry can be seen best in the case of the bio-ethanol industry. In the last decade, US bio-ethanol production increased almost tenfold due to the increasing demand for ethanol as a fuel additive (6.2 million m³ in 2000 and 50.1 million m³ in 2010 according to the Renewable Fuels Association). Worldwide bio-ethanol production rose from 65 million m³ in 2008 to 95 million m³ in 2010, an increase of almost 50% within only two years. However, one important drawback is that high volumes of bio-ethanol produce high amounts of effluents. The dry-grind bio-ethanol process from grains produces up to 5.6 t of stillage per m³ of ethanol (Drosch *et al.*, 2008). Since this process is the prevailing process in the USA, it can be estimated that roughly 280 million t/yr of stillage are accumulated in US domestic ethanol production. The state-of-the-art stillage treatment process is drying to animal feed. This consumes a considerable amount of energy, since grain silage has a water content of about 85–90%. Depending on the price of animal feed and energy, AD can be a valuable option. Using AD on the annual stillage produced in the USA, roughly 16,300 million Nm³/yr of methane could be recovered. In practice, the nitrogen and sulfur content of stillage can be a challenge for the stability of the AD process, although a stable process can be achieved through process optimization measures.

The main limitation for using industrial organic wastes for biogas production is related to their potential content of undesirable matter such as biological, physical or even chemical pollutants. Depending on the process of their origin, industrial wastes can contain physical impurities, pathogens, heavy metals or persistent organic compounds in such amounts that they could become sources of environmental pollution or pose health risks for humans and animals when the produced digestate is used as crop fertilizer. Environmental legislation, certification systems for digestate and ‘positive lists’ have therefore been introduced in many countries, prescribing limit values for pathogens and pollutants and requiring product declaration of the feedstock used and the digestate produced. Specific materials (e.g. food

residues, slaughterhouse and rendering wastes) must be sanitized prior to AD. More details about quality issues can be found in Chapter 12 of this book.

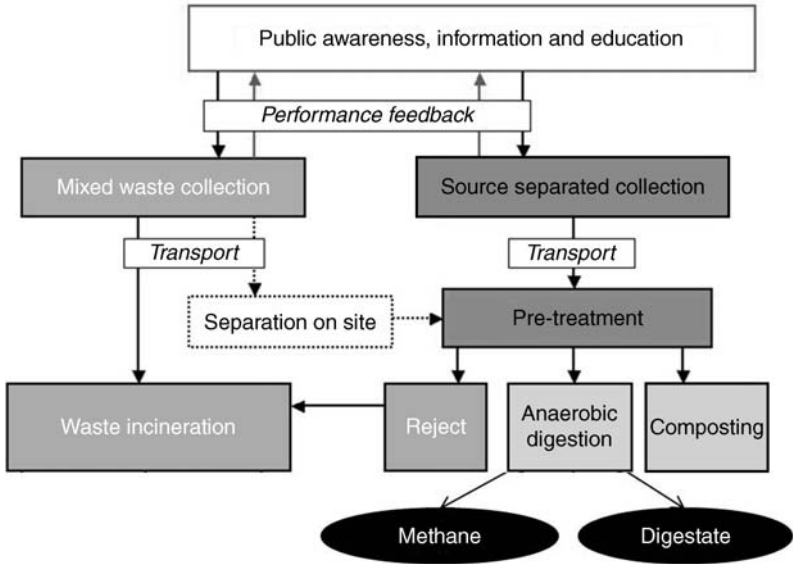
Another important limitation refers to a shortage of such organic wastes, especially methane boosters, in countries with well-developed biogas markets. It is likely that industrial organic wastes will continue to be used, when available and mainly because of their high methane yields, especially as co-substrates for animal manure. The environmental benefits related to AD and the high costs of other disposal methods are further incentives in favor of using suitable industrial organic wastes, by-products and residues as biogas feedstocks.

2.2.3 Municipal waste biogas feedstock

Source-separated organic waste

Source-separated organic waste refers to the organic fraction of household waste such as food waste, garden waste and other similar organic wastes, separately collected. Increasing urbanization and consumption patterns makes adequate waste management mandatory. Separate collection is a solution that is capable of providing clean and high-quality materials for use as AD feedstock, at the same time reducing the stream of organic materials going to landfills and incineration (Favoio, 2002; Rutz *et al.*, 2011) in favor of recycling and nutrients recovery. Separately collected organic household wastes are often co-digested with animal manure and slurries in manure-based AD plants. Increasingly high amounts of household wastes generated in society indicate a very high AD potential. The use of household wastes as a feedstock for biogas does not compete for land use and does not have negative sustainability impacts (Rutz *et al.*, 2011).

To be suitable for recycling as AD feedstock, organic household wastes must have high purity. Amon and Boxberger (1999) show that low-purity waste, due to the presence of foreign materials, can cause technical malfunctions of the biogas plant, be a source of pollutants and can have a negative impact on the utilization of digestate as fertilizer. For this reason, the authors indicate that the content of foreign materials in organic wastes may not exceed 0.1%. Effectively, this is only possible if organic wastes are collected separately, according to their composition materials, at their place of production or utilization. Separate collection is an integrated part of the overall waste management system, as shown in Fig. 2.2, and ensures the high quality and purity necessary for their optimal use as AD feedstock. Compared with source separation, mixed collection followed by a central separation implies higher costs and considerable losses of organic matter (Favoio, 2002) as well as high contamination risk. For this reason, the



2.2 Separate collection of digestible organic wastes is integrated in overall waste management.

application of digestate from mixed-waste collection onto agricultural land is not allowed in some countries.

Organic household wastes have a high biodegradability and methane yield. Their nutrient content is well balanced and favorable for the metabolism of anaerobic microorganisms (Zhang *et al.*, 2006). As household waste contains various pathogens, fungi and other biological vectors, sanitation is required for effective inactivation of the pathogenic matter.

The main limitation of separate collection of organic household waste as feedstock for AD is considered to be the apparently high cost of waste collection. Favoino (2002) indicates that, in fact, the costs of separate collection are comparable with traditional mixed-waste collection in cases when the performances of the collection schemes are optimized and if separate collection is an integrated part of the whole waste management system. Furthermore, a significant income of many biogas plants running on waste materials comes from gate (tipping) fees. Purity is another limiting factor in the utilization of source-separated organic waste as a feedstock for biogas production. The content of foreign materials depends to a very large extent on the human factor (Favoino, 2002), that is, the awareness and motivation of the population involved in collection systems. Favoino (2002) indicates that, even if purities higher than 90% are achieved, organic household wastes can contain significant amounts of disturbing compounds such as metal, glass, plastic and sand. In most wet digestion processes, these

compounds are removed through complex pre-treatments. In plug flow digesters or in dry digestion systems, the disturbing compounds can be removed also after digestion.

Sewage sludge

Anaerobic digestion used to treat primary and secondary sludge resulting from the aerobic treatment of municipal wastewater is a standard technology around the world. The technology is used in thousands of installations as part of modern treatment systems of municipal wastewaters. Sewage sludge has a methane potential similar to animal slurries (primary sludge has a higher methane potential than waste-activated sludge). Various pre-treatments can be applied to increase methane yield, aiming at disintegration of bacterial biomass and releasing organic substances easily accessible to the subsequent anaerobic degradation, for example mechanical disintegration, chemical hydrolyses, thermal hydrolyses and enzymatic degradation (Rulkens, 2008).

The limiting factor for the use of sewage sludge as biogas feedstock is the high content of pollutants and the risks related to their subsequent presence in digestate used as fertilizer. Because of its origin, sewage sludge contains significant amounts of biologic and chemical pollutants. Utilization of sewage sludge as feedstock for AD is therefore regulated by national legislation and quality standards for the utilization of waste products as fertilizers. There are countries in which the use of digested sewage sludge as a fertilizer or for other agricultural purposes is banned, while in other countries its utilization as a fertilizer is controlled by strict requirements concerning the limit values of concentrations of heavy metals and persistent organic pollutants as well as the sanitation requirements for inactivation of pathogens and other biologic vectors (Smith, 2011). Sewage sludge is often co-digested with manure or/and organic wastes from industries and households, which improves the biogas yield and the process stability (Kuglarz and Mrovec, 2009). More details about sewage sludge can be found in Chapter 12 of this book.

2.2.4 Aquatic biomass

Along with the materials produced by different sectors of society described so far, there is growing interest in the utilization of aquatic biomass from marine and fresh waters. This is estimated to have high potential for utilization in food and feed production and as a raw material for various other industries, and is also one of most promising feedstocks for biofuels production, including biogas (Burton, 2009; Wellinger, 2009; Angelidaki *et al.*, 2011). In the last few decades, research on aquatic biomass has

Table 2.5 Productivity data of some macroalgae

Macroalgae species	Biomass yield (t/ha/yr dry)	Location	System	Observations
<i>Ulva</i> sp.	22.5	Pennsylvania, USA	Cultivated	Estimations based on 6 months' growth
<i>Ulva</i> sp.	45	Denmark	Cultivated	Extrapolation of 4-month trial
<i>L. japonica</i>	25	China	Cultivated	Commercially achieved yield
<i>L. japonica</i>	60	Japan	Cultivated	Dry and ash-free value
<i>L. hiperboria</i>	30	Scotland	Natural stock	Requires rest of > 5 years between harvests
<i>Laminaria</i> , <i>Gracilaria</i> multicrop	45	Southern USA	Cultivation	Optimized production
Red, green, brown multicrop	50	North Sea	Cultivation	Theoretical yields

Source: Data compiled after Burton (2009).

intensified and, according to Wellinger (2009), research in this domain will increase even further in the coming years and will switch from the purely academic towards demonstration projects supported by power industries interested in finding alternatives to rapidly decreasing oil reserves and solutions for reduction of greenhouse gas emissions and carbon sequestration. Aquatic biomasses are feasible for wastewater remediation and generate high biomass yields. Two groups are of interest for the biogas sector. The first is represented by macroalgae, commonly referred to as seaweeds, which are rich in natural sugars and other carbohydrates, are known for their high biomass yields (Table 2.5) and have an important role in supporting aquatic biodiversity.

The second group is microalgae – a heterogeneous group of microscopic photosynthetic organisms, mostly unicellular, living in marine or fresh waters. Of the over 30,000 species of microalgae known worldwide, only a few are of actual commercial interest, including *Chlorella*, *Spirulina*, *Dunaliella* and *Haematococcus* (Wellinger, 2009). Green microalgae, known as diatoms, are considered the most suitable for energy and biogas and other biofuels production, as well as for the production of high-value materials. Microalgae have high photosynthetic efficiency and are rich in lipids. One of the limitations of microalgae is their very low dry matter content. In generating biodiesel for example, water needs to be removed to allow bioesterification of the lipids. The removal of water is energy

intensive, but for biogas production, generation of a dry matter content of around 8% may be sufficient.

There are promising research results and some full-scale applications around the world using aquatic biomass as a feedstock for biogas production, but technological solutions to some issues are still in the research phase.

2.3 Characteristics of biogas feedstock

2.3.1 Suitability and availability

The substrates used in practice for biogas production are selected based on their suitability and availability. Suitability in this case is defined by a number of characteristics and parameters such as the content of easily digestible organic matter, methane potential, particle size, dry matter content, pH, C:N ratio, the content of macro- and microelements, etc. Availability means that the feedstock is easily accessible for biogas plant operators and can be supplied in sufficient amounts on a renewable basis. The values of some basic parameters of feedstocks commonly supplied to European biogas plants are illustrated in Table 2.1. The biomass resources suitable as feedstocks for biogas production vary significantly in terms of composition, digestibility, methane potential, dry matter content, content of nutrients and other characteristics. The importance of these characteristics is that they can be used to optimize the AD process and methane production. Most AD processes run optimally at neutral pH (around 7), and a C:N ratio of the substrate mixture between 20:1 and 30:1. As the anaerobic microorganisms inside the digester need to be supplied with some basic 'ingredients' necessary for their metabolism, it is common practice to mix more than one feedstock (co-digestion) with the aim of obtaining a balanced substrate composition and a synergic effect of improved process stability and higher methane yield (Angelidaki, 2002). Evaluations of the suitability of biogas feedstocks are presented in Chapter 3 of this book.

2.3.2 Digestibility

Digestibility is the main AD feedstock parameter, with direct influence on methane production, and refers to the ability of the substrate to be decomposed through AD (see Table 2.2). The digestibility of a certain material depends on its content of easily digestible compounds like simple sugars. However, biogas feedstock can also contain various amounts of low digestible compounds, known as recalcitrant matter, such as lingo-celluloses. Steffen *et al.* (1998) noted that the anaerobic degradation rate varies significantly with feedstock composition. Feedstock composition also

determines the amount of time necessary to decompose a specific feedstock and thus the necessary retention time of the feedstock inside the digester. Low molecular weight carbohydrates, volatile fatty acids and alcohols are digested in hours; proteins, hemicelluloses and lipids in days, while cellulose needs several weeks to be decomposed in anaerobic conditions. Feedstock substrates consisting of fats and oils, known for their very high methane yields, require longer retention times and larger digester volumes compared with substrates rich in carbohydrates and proteins. In practice, for economic reasons, digesters are operated with the shortest retention times and the highest methane yields possible.

2.3.3 Impurities with disturbing effects

Together with the supplied feedstock, various unwanted components can be accidentally supplied to the biogas plant. Once they enter the digester, their presence can cause perturbations of the normal operation. Common problems are reduction of the active volume of the digester (caused by sedimentation of sand on the bottom of the digester), process failure through foaming, phase separation and floating layers, or even damage to machinery such as pumps, caused by metallic impurities or other disturbing components.

The most common disturbing material is sand, often supplied with animal manure. Light materials such as straw and wood particles may cause floating layers and perturbations of the fluid dynamics. The presence of straw can also have disturbing effects, although this depends on particle size: small-particle straw does not disturb the process and can improve the methane yield considerably (Steffen *et al.*, 1998). Inorganic materials such as glass and metal scrap, polymeric compounds like plastics (often supplied with biogenic wastes) and salts and fatty compounds present in some industrial wastes are also considered disturbing components (Table 2.6).

Once they occur, disturbing effects are difficult to control. For this reason, all feedstock types must be carefully selected and those containing disturbing components must be avoided or properly pre-sorted before being fed to the digester. The classic example is organic household waste, which is best separately collected (source separation) in order to obtain the required purity and guarantee trouble-free AD and high-quality end products.

2.3.4 Inhibitors

Some compounds in the feedstock (and thus supplied to the digester with the feedstock) can have a negative effect on the microbiology inside the digester, causing imbalance or complete cessation of microbiological activity in the worst case (see Table 2.6). These are named inhibitors and their inhibitory effect depends to a large extent on their concentration in the feedstock

Table 2.6 Specific feedstock compounds and their effect on the AD process (digestibility, disturbing effects and inhibitory effects)

Compound	Digestibility	Feedstock source	Process disturbing effects	Process inhibition
Fats	Very good	Slaughterhouses Rendering plants	Foaming Layering Poor water solubility	High VFA levels Low pH
Proteins	Very good	Dairy processes Pharmaceutical industry	Foaming	pH decrease High ammonia concentrations
Carbohydrates		Agro-industries	Foaming	pH decrease
Sugars	Very good	Crop residues	Lignin	
Starch	Very good	Animal manures	incrustation	
Cellulose	Poor			
Volatile fatty acids (VFA)	Very good	Rendering plants Oil mills	Poor water solubility	High VFA levels
Organic pollutants	Poor	Animal manures Crop and crops residues	Foaming	Antibiotic effects
Pesticides		Organic wastes		
Antibiotics				
Detergents				

Source: Adapted after Steffen *et al.* (1998).

mixture, but also on other local conditions inside the digester (Steffen *et al.*, 1998). For example, an increased amount of volatile fatty acids (VFA) can cause process imbalance if their concentration inside the digester exceeds the pH buffer capacity of the AD process, reaching so-called shock-levels (Steffen *et al.*, 1998). Increased levels of VFA can occur as a consequence of rapid degradation of large amounts of organic macromolecular matter (lipids, carbohydrates or proteins). In ‘healthy digesters’, microbial adaptation to increased concentrations of VFA occurs eventually. High concentrations of end products such as free ammonia can also have inhibitory effects through accumulation inside the digester. Residual amounts of antibiotics, disinfectants, pesticides and toxic compounds like heavy metals can be supplied with agricultural feedstock or organic wastes as shown in Table 2.6, but their inhibitory effect is reported by Steffen *et al.* (1998) to be minor. Their presence in digestate can nevertheless compromise its amenability as crop fertilizer. Information on the evaluation of possibly inhibitory feedstock can also be found in Chapter 3 of this book.

2.3.5 Feedstock as methane yield boosters

The group of methane yield boosters includes compounds belonging to various feedstock categories, all having the common features of very high methane potential (Table 2.1). Methane boosters are supplied to biogas plants for economic reasons and are added in rather small amounts, precisely dosed, to the feedstock mixture, with the purpose of increasing the methane yield per volume of digested biomass. As with any biogas feedstock, it is important that methane boosters are of high quality, as their addition to the feedstock mixture will affect both the quantity and the quality of biogas production. Frequently used methane boosters are fatty materials such as fish oil from fish processing industries, soya bean oil and margarine from the food industry and various alcohol residues from brewing industries. Along with these, residues from the sugar and beverage industries are also used to enhance methane yields of the substrate mixture. More recently, glycerin from biodiesel production was introduced as a biogas feedstock and methane booster to the group of so-called oleochemicals. Use of glycerin as a feedstock for biogas is part of the concept of integrated biorefinery in which by-products from biofuels production (such as glycerin and press cake from the production of biodiesel) are further processed through AD with the extraction of methane. The press cakes remaining after pressing juice or oil from grapes, olives, apples and other fruits are also a good and homogeneous biogas feedstock. These press cakes contain the skins, pulp, seeds and stems of the pressed fruits. Compared with other feedstock types, the industrial wastes used as methane boosters are highly homogenous materials. They can be added to the digester in precise small amounts and their effect on the microbiology inside the digester and on the methane yield is easily predictable. In general, certain upper limits for the addition of methane boosters to the feedstock mixture inside the digester are recommended as excessive amounts negatively influence the AD process.

2.3.6 Feedstock influence on plant operation

The characteristics and composition of the feedstock influence the configuration, design and operational parameters of an anaerobic digester. The feedstock also determines the quality and quantity of biogas and digestate produced, and therefore has a direct impact on the overall economy of the biogas plant. The composition of the feedstock that is to be digested is one of the most important elements in determining the size of the digester and thus the investment cost of the plant, as longer retention times require a larger digester volume. The feedstock supplied determines to a large extent the main objective of the AD treatment. The digestion of animal

manure and slurries in biogas plants is, in most cases, motivated by the environmental and farming benefits delivered by manure management and the avoidance of negative environmental impacts from animal production. For source-separated household waste, the primary aim is sustainable waste management, waste reduction and recycling of organic matter. For wastewaters, the objective is often removal of their organic load in order to facilitate further disposal. In the case of energy crops, the main aim of AD is production of renewable methane.

2.3.7 Feedstock description and declaration

Each type and load of feedstock supplied to a biogas plant should be accompanied by documentation containing a detailed description of the material, provided by the feedstock producer. The following basic information must be included as a minimum.

- Origin. The name and address of the feedstock producer and supply company where these are not one and the same, which process the waste originates from and the raw materials or original processed materials used in the process.
- For household waste, the area from where waste was collected, whether or not it is source-separated and type of collection containers used (plastic bags, paper bags, bins, other).
- Methane potential.
- Chemical composition (pH, dry matter, organic dry matter, macro- and microelements).
- Contamination (chemical and biological).
- Description (color, texture, consistency, smell, etc.).
- Potential hazards related to handling, storage or recycling as fertilizer.
- Particle size.
- Availability (amount and length of time material of the same quality is available).

The feedstock description and declaration is an official document that should be archived at the biogas plant. The producer is responsible for supplying feedstock in conformity with the declared quality, which should be controlled at the biogas plant. All feedstock types should be analyzed and tested regularly in order to maintain quality standards and adhere to the legal requirements for feedstock quality. Feedstock quality management is an important measure intended not only to avoid any possible AD process inhibitions, operational disruptions or heavy wear of the biogas installation components, but also to prevent any actual or future threats to human and animal health and the environment caused by introducing unwanted

materials and compounds to the biogas cycle. The feedstock declaration and sample taking procedures are detailed in Chapter 3.

2.4 Resource availability and supply chain issues

The worldwide biogas bioresource is often defined as the theoretical, technical, economic and ecological potential. Many bioresource studies have been undertaken by researchers, policy makers, NGOs and interest groups. These studies range from global, national and regional to local scale as well as from general biomass assessments to studies only focusing on biogas production.

The use of the existing biomass potential for biogas production is generally limited by natural and human-made causes as well as by the annual natural biomass regrowth. Of main relevance for a commercially viable biogas plant is the local potential and availability of a suitable biomass feedstock within a certain area around the plant to ensure continuous, stable and economically sustainable operation of the plant. The potential of biogas feedstocks is therefore influenced by their spatial distribution and depends on the feedstock type. In the case of wastes such as municipal solid wastes (MSW), agricultural wastes, food wastes or industrial wastes, availability is limited by the quality and purity of the waste. In many countries, the main challenge is therefore to introduce sustainable waste collection and separation systems (sustainable in terms of energy balance and ability to provide overall CO₂ savings), which would increase the availability of organic wastes for AD (Rutz *et al.*, 2011). Furthermore, adequate political framework conditions are needed to make the theoretical potential also economically attractive. Utilization of waste products as a feedstock for biogas is generally sustainable and does not compete with other potential utilizations or with land use (Singh *et al.*, 2010), which is a major concern in the case of energy crops (Fig. 2.3).

One important issue related to the use of agricultural wastes such as dung and solid manure is related to the local availability of animal farms that keep livestock in stables. Animal droppings on grazing pastures can rarely be used for AD, except in developing countries. Furthermore, due to the generally lower energy content and diluted nature of farm wastes, there are economic limitations with respect to sustainable biomass transportation distances. The main limitation of energy crops specifically grown for biogas production is related to lower sustainability than biogas from residues (Korres *et al.*, 2010) and to land use issues related to competition with food production. This is of concern in many regions of the world, but especially in poor countries or those suffering from food shortages. In most European countries, there is currently overproduction of agricultural commodities, much of which is exported (EC, 2012), and it has been estimated that there is



2.3 Maize crops grown for biogas production in Germany.

enough potential to setup biogas plants based on energy crops without affecting European food supply (Smyth and Murphy, 2011).

These limitations influence the local availability of suitable feedstocks and thus feedstock logistics and biogas plant location.

2.4.1 Organizing biomass logistics

The logistics of biogas feedstock and digestate are determined by the feedstock types used in the biogas plant. The characteristics of the feedstock and the digested effluent (digestate) related to energy content, density, state of aggregation (liquid/solid), seasonality and hygienic aspects determine the logistical concept and auxiliary components of the biogas plant such as

- distance between feedstock source and biogas plant
- distance between biogas plant and digestate use
- suitability of road access
- transport system
- storage facilities for feedstock and digestate
- hygienic safety measures
- digestate application on the fields.

The distance between the feedstock source and the biogas plant should be as short as possible. Long transport distances and associated transport costs have negative impacts on the economics of biogas plants. The literature indicates that, due to low energy content per volume transported, it is not

economically or energetically sustainable to transport feedstock such as animal slurries further than 5 km and energy crops further than 15 km (Epp *et al.*, 2008). This means that a biogas plant processing these types of feedstocks should be located inside an average radius of 15 km from the available feedstock. In many cases, agricultural biogas plants are built in the proximity of animal farms so that liquid animal slurries can be piped directly from the livestock sheds to the plant. For other feedstock types such as the organic fraction of MSW or catering waste, the economically sustainable distances of biomass transport are often determined by the waste collection systems and the gate fees for the waste treatment. When large amounts of agro-industrial wastes are available at one place, AD facilities could be set up at the agro-industrial site, with the advantage of very short transport distances for which even piping systems could be used.

Apart from the distance between the feedstock source and the biogas plant, the transport of digestate has to be considered. For the most common use of digestate as agricultural fertilizer, it is also recommended to only transport digestate within a radius of about 15 km around the biogas plant (Epp *et al.*, 2008). However, in areas with a high concentration of agriculture and problems of over-fertilization, digestate may be transported further. In order to reduce transport costs, additional treatment of digestate, such as liquid–solid separation or drying may be suitable alternatives. If liquid–solid separation is used, the solid fraction may be further composted and sold as compost or used on agricultural or landscape areas. The liquid fraction can be further processed and used as nitrogen-rich liquid fertilizer. A good overview on different options for digestate treatment is given by Fuchs and Drosig (2010) and more details are available in Chapter 12 of this book.

Feedstock storage serves primarily to compensate for the seasonal fluctuations of feedstock supply. It also facilitates mixing different co-substrates for continuous feeding of the digester (Al Seadi *et al.*, 2008). The type of storage facilities depends on the feedstock used. Storage facilities can be bunker silos for solid feedstock like maize silage (Fig. 2.4), often covered with plastic sheets to minimize the exposed face, and storage tanks for liquid feedstock, frequently used for liquid manure and slurries. Usually, bunker silos have a storage capacity of more than one year while for storage tanks it is usually several days. Details on ensiling of substrates can also be found in Chapter 4 of this book.

The dimensioning of storage facilities is determined by the quantities to be stored, delivery intervals and the daily amounts fed into the digester. Depending on the logistical concept, feedstock storage facilities as well as digestate storage facilities may be located at the biogas plant or decentralized in the agricultural surroundings of the biogas plant, which is more often the case for digestate storage. Decentralized storage of feedstock



2.4 Bunker silo for storage of solid feedstock.

and digestate at several smaller storage facilities may be a good option for very large biogas plants or for plants where very large transport distances are involved. This allows, on the one hand, the use of larger trucks for efficient transport between the biogas plant and the storage facility and, on the other, the ability to use smaller agricultural field vehicles that are not too heavy and do not lead to soil compaction.

The logistics of the digestate are influenced by its anticipated use and further treatment. When digestate is used as fertilizer, its storage facilities have to be large enough to meet national requirements such as fertilization regulations. In Europe, a minimum storage capacity of six months for digestate is required in most countries. This allows good fertilizer management in the framework of good agricultural practices. Figure 2.5 shows a storage facility for digestate in the Lemvig area of Denmark, located in the vicinity of the fields where digestate is to be applied as fertilizer.

The type of feedstock, size of the biogas plant and the size of the transport vehicles all influence the needs for transport infrastructure, meaning access and suitability of the roads that are mainly used. Improperly planned road access can lead to negative impacts such as deviations due to restricted road access for heavy transport and agricultural vehicles, and conflicts with neighboring residents.

The vehicles used for the transport of biomass differ according to the characteristics of the transported materials. Animal slurries, liquid manures, liquid wastes and liquid digestate are usually transported by vacuum tankers (Fig. 2.6). Solid wastes are transported by bin lorries, while energy crops are



2.5 Digestate delivery to post-storage tanks located close to the agricultural fields (source: Lemvig Biogas, Denmark).



2.6 Vacuum tanker unloading raw animal slurry in the closed receiving hall of a biogas plant (source: Lemvig Biogas, Denmark).

usually chipped into small particles during the harvesting process and are then transported by agricultural trailers to the biogas plant for subsequent ensiling. From an economic and energy consumption point of view, large transport vehicles are preferable, although the weight of large vehicles can lead to serious soil compaction of agricultural fields during harvesting of energy crops. Soil compaction depends on the axle load, tyre type and size

and air pressure. In order to save fuel and to reduce soil compaction on the field, it is recommended to have as low tyre pressure as possible. On the other hand, it is recommended to have high tyre pressure on roads. Thus, several tractor and truck manufacturers are currently working on automatic tyre pressure adaptation systems. Furthermore, for digestate application, new pipe systems have been developed that allow pumping the digestate directly up to 1 km to the tractors on the fields; this negates the need for heavy tanker trailers.

The feedstock type also influences auxiliary equipment at the biogas plant, namely the requirements of eventual safety equipment for avoiding the spreading of pathogens. The use of waste materials often requires special hygienic measures, for example sanitation of the feedstock at higher temperatures for a certain period of time. The feedstock transport vehicles for transporting waste materials also need to be cleaned as mandated by national legislation. In centralized co-digestion plants, a common system largely used in Denmark where feedstock is supplied from several livestock farmers, the cleaning and disinfection of transport vehicles is an important issue in order to avoid spreading pathogens and diseases from one farm to another.

Finally, every biogas plant needs equipment for measuring mass flows; this usually includes truck scales or mass flow meters for pumpable feedstock. The inputs and outputs of biogas plants need to be standardized for management of revenue. It is mandated to keep records of the mass flows for electricity feed-in tariffs systems or for gate fees for waste treatment.

A very different approach is transport through the wastewater collection system, as in some parts of North America, where organic kitchen waste is sized in garbage disposal units installed under kitchen basins (EPA, 2012). The waste is then conveyed to a wastewater treatment plant, which may include an AD facility. About 50% of households in the USA use such waste disposal units. This system is not implemented in Europe due to infrastructure problems related to the capacity of wastewater treatment plants, high water consumption and problems related to further treatment and use of digestate.

2.4.2 Influence of biomass logistics on location of the biogas plant

The choice of location for setting up a biogas plant is determined by the feedstock logistics and the availability of feedstock. Distances of feedstock supply and road access are the main elements to consider when selecting the location of a biogas plant. Along with these, other general aspects that should be considered include

- the size and ownership of the property
- classification of the property in official spatial plans
- legal aspects, including the required permits
- dedicated characteristics of the site
- access to necessary infrastructure
- opportunities to sell the heat
- vicinity to neighbors
- competition with other biogas plant operators and farmers.

The size of the property depends on the size of the plant and clearly must be large enough. Eventual extension of the plant at a later stage should be considered in the initial planning phase. A 500 kW_{el} agricultural biogas plant requires about 4000 m² for the digesters, gas storage, electric generator and auxiliary facilities. If the biogas plant is operated with energy crops (e.g. corn silage), seasonality of the feedstock (in central Europe corn is harvested only once a year) requires an additional 5400 m². Thus, a biogas plant of 500 kW_{el} would need a total of about 1 ha. This figure is only a guiding value, as the actual area requirement also depends on the chosen technology. Plants that operate on a just-in-time delivery, which applies to biogas plants continuously using manure or MSW, need much smaller areas. Moreover, the produced digestate requires on-site storage. In many countries, digestate and any other fertilizers can only be applied during the vegetation season and must therefore be stored during winter in specially established storage facilities. Such a storage facility for a 500 kW_{el} plant requires an additional 4 ha.

Potential sites for biogas plants should ideally be owned by the plant operator or operating company. Often, this is also a precondition of investors and financing bodies. Long-term land leasing contracts may be also an option. If the site is already owned by the biogas plant operator (e.g. farmer), the use of existing infrastructure (e.g. houses, bunker silos, etc.) may be used for the biogas plant and may increase the economy of the plant if this infrastructure is already amortized.

Spatial plans provide information on the classification of the land that may be potentially used for a biogas plant. Depending on the applied legislation, the land may be classified as a conservation area, an agricultural area, a settlement area, site value too high to use for biogas facility or an industrial site. It must be considered that the procedure for setting up a biogas plant in a conservation area is more time consuming and more expensive (if it is allowed at all) than for an industrial area. Conservation areas may include water protection areas, landscape conservation areas and high biodiversity areas. Generally, the use of agricultural or industrial land, or even degraded land, is preferred. Closely related to land classification are the requirements for getting the permits. The costs and the duration of the



2.7 Lemvig Biogas plant (source: Lemvig Biogas, Denmark).

permitting procedure therefore have to be considered. This depends on local legislation and regulations.

Dedicated characteristics of the site include the suitability of the soil for construction as well as the topography of the site. In general, construction (e.g. digesters, generator house) requires level surfaces but in some cases sloped properties can be beneficial for insulation purposes of the biogas digesters or for pumping the substrate. Sites exposed to risks of earth or snow slips must be avoided. Sites with a high groundwater table and/or the potential for flooding must be evaluated. Leakage from feedstock storage facilities to natural water bodies or groundwater should always be avoided, especially in protected groundwater areas or drinking water catchment areas. The main wind directions should be considered if neighbors are close to the facility due to odor nuisances. Figure 2.7 shows a panorama image of the location of Lemvig Biogas Plant, Denmark.

Access to infrastructure has been mentioned already in relation to road access. Other infrastructural requirements concern access to the electricity grid and/or to the natural gas grid in order to reduce high connection costs. This applies to both biogas plants selling electricity or injecting methane into the natural gas grid. Access to drinking water supply and to sewerage systems may be needed, in case wastewaters (e.g. from cleaning tanks and trucks) cannot be treated in the biogas plant. For biogas plants using the gas for electricity production, it is important to locate the plant close to potential heat users (local industries, greenhouses, households, etc.). Utilization of excess heat from the production of electricity has an important contribution to the economic sustainability of a biogas plant.

Finally, a biogas plant requires public acceptance, especially if it is located

close to settlements. Problems are inversely proportional to the distance separating a plant from its neighbors. Minimum distances need to be considered. Potential conflicts are usually related to odor emissions, noise and increased transport. The dirtying of roads is also an important issue, especially during harvesting seasons of energy crops. In some regions where mainly corn is used as feedstock (Germany), negative perception is placed on the increasing number of corn monocultures. Intercropping with sunflowers, for example, may reduce this perception. Involvement and communication with neighbors during the planning phase is therefore a must. A recent increasing concern in regions with a high density of biogas installations, as is the case in some regions of Germany, is potential competition with other biogas plant operators and farmers. This includes competition on leaseholds for energy crop production, which may increase lease prices for agricultural land. In the case of biogas plants using organic waste, the competition for waste material as a feedstock is also increasing.

2.5 Conclusion

There is a large variety of biomass types and categories suitable as feedstocks for the production of biogas using AD. Each feedstock material is defined by specific characteristics and parameters, which are technically described in Chapter 3 of this book. Each has benefits and limitations, influencing suitability, local availability as well as overall biomass logistics and biogas plant location. Nowadays, agricultural by-products such as animal manures, crop residues, organic wastes from food and feed industries and municipal and household wastes are valuable feedstock materials for biogas production. In the last decade, energy crops have been added to this list of biogas feedstocks. The industrial sector also uses biogas technologies to treat organic-loaded wastewaters and to recover energy.

It is estimated that the use of conventional crops for energy could be increased in the medium term – with careful consideration of land availability and food demand – on marginal, degraded and surplus agricultural lands. In the longer term, aquatic biomass may prove to have potential as a valuable energy feedstock, including for biogas. In the short term, attention will probably focus primarily on increased recycling and utilization of agricultural by-products and residues, of which animal manures and slurries have the largest potential, as well as towards the use of suitable organic wastes from households and municipalities generated by the ever-increasing world population.

The limited agricultural area and the price fluctuations of energy crops will increase the need for research into modern agricultural systems with high productivity and improved sustainability. Intercropping and mixed cropping systems, the use of new energy crops and breeding efforts will be

key challenges that need to be supported by internationally integrated research programs and favorable policy frames. In the industrial sector, the utilization of AD technologies for energy recovery from by-products and wastes will increase in the future with the aim of reduced energy costs, cleaner technologies and sustainable waste management. There is still significant potential to expand the use of biomass for biogas production because of the large volumes of unused residues and wastes. In addition, the expected future development of the sector of biofuels and biorefineries will produce large amounts of by-products, for which biogas technologies are valuable options.

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Complementary information about biogas feedstocks and their characteristics, technical parameters and analyzing methodologies can be found in Chapter 3. Further information can also be found from the following sources.

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Analysis and characterisation of biogas feedstocks

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Abstract: The abundance and variety of possible feedstocks for biogas plants necessitate detailed characterisation and evaluation of specific feedstock types. Feedstock characterisation requires reliable feedstock analysis. This chapter describes in detail the different feedstock analysis methodologies. The following essential analyses are described in detail: pH, total solids/dry matter, volatile solids/organic dry matter, chemical oxygen demand, total Kjeldahl nitrogen, ammonia nitrogen and biochemical methane potential. Additional analyses on biogas feedstocks are described, including total organic carbon, trace element analysis, sulphur, phosphorous and continuous anaerobic fermentation tests. Important details for feedstock evaluation are described. Firstly, different approaches for estimating a realistic energy recovery potential are laid out. Secondly, the effect of the carbon oxidation state in a feedstock on methane concentration in the produced biogas is described. Thirdly, the availability of macro- and micronutrients is estimated and a short summary of possible inhibitory or toxic components in biogas feedstocks is given.

Key words: biogas, anaerobic digestion, feedstock analysis, feedstock characterisation.

3.1 Introduction

There are many organic materials available in significant quantities that can be used as feedstock for anaerobic digestion, such as waste fractions,

industrial by-products and energy crops. Waste fractions include the organic fraction of municipal solid waste, source-separated organic wastes, food and feed leftovers, kitchen waste and grass cuttings. In industrial processes, significant quantities of organic by-products are accumulated, including agro-industrial by-products (manure, harvest residues, etc.) and food processing by-products (e.g. slaughter house wastes, whey, brewers' spent grains, distillery slops, fruit and vegetable wastes, sugar beet residues). High-strength industrial wastewaters can also be of interest as feedstock in biogas plants. Finally, purpose-grown crops for anaerobic digestion include maize, grass and beets.

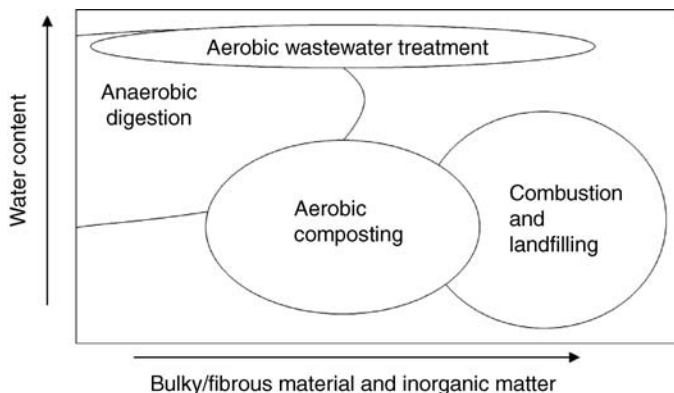
Not all waste products and crops are equally suitable for biogas production and in some cases biogas production might not be profitable. To assess the suitability and profitability of biogas feedstocks, a reliable way of characterising and analysing feedstocks is necessary. A preliminary assessment of a feedstock can be carried out using data available in the literature combined with feedstock process and production data. Legal issues should also be considered, such as environmental and safety laws regulating the use of waste products. If the preliminary assessment indicates that the feedstock might be suitable, a detailed laboratory analysis should follow. Concise information about the different analysis methods (such as total solids (TS), volatile solids (VS), nitrogen content, chemical oxygen demand (COD)) and their limitations are discussed in this chapter. Furthermore, the availability of macro- and micronutrients should also be evaluated, as well as the possibility of the accumulation of inhibitory substances (antibiotics, heavy metals, disinfectants, ammonia, hydrogen sulphide, etc.). An important test for the anaerobic degradability and acceptability of a feedstock is a batch test for the biochemical methane potential (BMP). The best information on the behaviour of a biogas feedstock in a biogas plant can be obtained from continuous fermentation trials. However, a major disadvantage of these continuous trials is their complexity and cost.

After a detailed characterisation of the biogas feedstock has been carried out and if the results seem promising, a detailed economic evaluation should follow. This is essential before realising a biogas project. Feedstock analysis and characterisation allow estimation of the price of a substrate when sold to a biogas plant operator.

3.2 Preliminary feedstock characterisation

3.2.1 General suitability as feedstock for anaerobic digestion

Using basic data such as water content and content of inorganic matter or bulky/fibrous material, a rough estimation of the suitability of a specific



3.1 Overview of feedstock suitability for different treatment technologies.

material as a feedstock for biogas production can be carried out (Fig. 3.1). Feedstocks with considerable water content and a low amount of inorganic matter or bulky/fibrous material are ideal for anaerobic digestion. In contrast, if the amount of inorganic matter or bulky/fibrous material increases and water content is rather low, aerobic composting is generally preferred. If the inorganic matter or bulky/fibrous material is even higher, combustion (for energy recovery) or landfilling (for inorganic wastes) is preferable. In addition, for feedstocks with a very high water content, aerobic wastewater treatment is generally applied. This overview is a very simplified approach and more detailed substrate evaluation follows later in this chapter.

3.2.2 Feedstock production and process data

Process data of a possible feedstock should be available if anaerobic digestion is to be integrated into an existing process such as high-strength wastewater treatment or if an industrial by-product is to be digested. These data could include quantity, water content, composition and temperature. However, the available information can be very limited in many cases since the available feedstocks are often of little value (e.g. waste products). Nevertheless, continuous process data can often be better than some simple samples because these data also account for changes in feedstock composition (e.g. after changes in the process or after a cleaning procedure). In the case of many organic wastes there can also be a lot of information available because many waste products have to be analysed and declared before being transported or sold.

Amount and water content of feedstock

An important piece of information about a feedstock is the amount produced or accumulated per year (or season). This information can be used to estimate if sufficient feedstock is available for treatment in a centralised plant. The water content of a feedstock (liquid, paste-like/semi-solid or solid) is also important first-hand information.

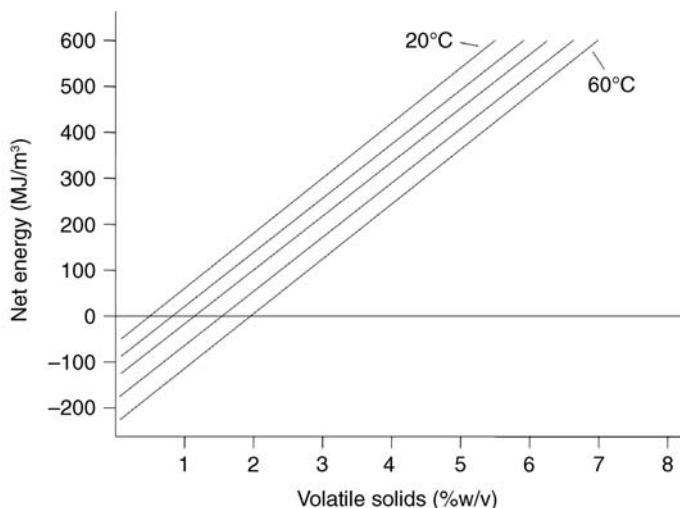
Seasonal variation of feedstock accumulation and composition

In general, a biogas plant is operated all year round. If the feedstocks are only seasonally available, they must be storable. Some feedstocks like crops can be ensiled for storage. However, in industrial processes that work in a campaign (e.g. sugar beet factories), the energy will also be needed during the campaign. In this case, a biogas process would have to be adapted to operate during the campaign and to stop for the rest of the year. Although this is not a state-of-the-art operation mode of biogas plants, it is a viable possibility.

The composition of other waste fractions (municipal organic waste for example) can also vary due to seasonal changes. One example is organic waste produced in suburbs – its composition can depend on the seasonal change in gardening activities. For example, during the summer the waste may contain grass cuttings, which are replaced by hedge prunings in the winter. This has an obvious effect on the carbon to nitrogen (C:N) ratio.

Feedstock temperature

The temperature at which a feedstock will enter the biogas plant can be important information (Braun, 1982). This is especially the case if the biogas process is integrated into an existing process rather than being transported long distances or stored for a long time. In addition, the local climate is of relevance since the heating demand of the digester depends on the outside temperature. Very low temperatures of the feedstock combined with high water content cause a high heating demand. As a consequence, the net energy output of a biogas process can decrease substantially. Figure 3.2, shows the relationship between VS content, fermentation temperature and net energy for a substrate temperature of 5°C. According to this figure, a slurry of 1% VS at 5°C would not yield any energy when fermented at 40°C. Heat exchangers can be applied to improve the energy balance, but this increases investment costs. Apart from low temperatures, if the feedstock temperature is too high, this can have a negative effect on the microbes in the digester. Therefore, feedstocks at very high temperatures occasionally will have to be cooled down before entering a biogas plant.



3.2 Net energy yield of a feedstock at 5°C depending on volatile solids content and fermentation temperature (source: Braun R (1982) *Biogas – Methangärung organischer Abfallstoffe*. Springer, Berlin, Germany; Figure 37 on p. 100; with kind permission from Springer Science +Business Media B.V.).

Data on feedstock characteristics in the literature

The literature provides detailed data tables for various biogas feedstocks. Although these data can differ significantly, they do provide very valuable first-hand information. A table of the characteristics of many different biogas feedstocks can be found in Chapter 2 of this book. Feedstock characteristics are also given by Braun (1982), Bischofsberger *et al.* (2005), Braun (2007) and Murphy *et al.* (2011).

3.2.3 Legal classification of feedstock

Before using a certain substance as a feedstock in a biogas plant it is of importance to evaluate the legal consequences of using this feedstock. There are two main legal issues that should be stressed at this point – pollution control and biogas subsidies.

Pollution control

The utilisation of feedstocks considered as waste material or wastewater is strictly regulated due to pollution control measures. In particular, utilisation of the biogas by-product, the digestate, is regulated. It can be assumed that chemical contaminants (e.g. heavy metals, polycyclic aromatic hydrocarbons (PAHs), dioxins) if they enter a biogas plant via the feedstock will

mostly remain in the digestate. The reason for this is that only a limited amount of chemical contaminants are anaerobically degradable. In addition, the contaminant concentration based on TS will even increase, as TS are degraded in the biogas plant. Therefore, in order to increase the quality of the digestate, the input materials of biogas digesters should be tightly regulated. In many countries, there is an additional legislative issue. If substances that are legally considered wastes enter a biogas plant, the whole digestate is to be treated according to waste legislation. If, for example, municipal food waste is mixed with grass silage, which is not a waste pre-digestion, then the digestate from the mixture is then considered a waste. This applies even if there are no pollutants in the digestate. In countries such as Denmark, digestate produced from feedstock mixtures that comprise up to 25% organic wastes (with the exception of stomach and intestine contents from slaughterhouses, which are equivalent to animal manure) is considered animal manure, and its use is controlled by manure and slurry regulations. If the amounts of wastes co-digested are above this limit, the digestate is considered waste and its use (as fertiliser for example) is governed by sewage sludge regulations.

Biogas subsidies

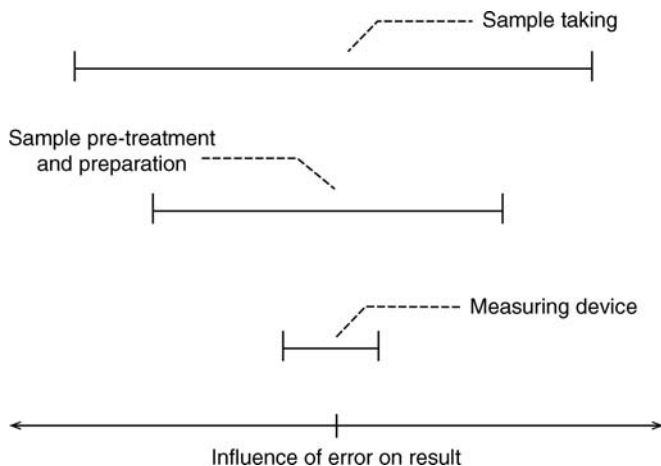
Biogas is subsidised by some countries due to its high production costs. Different subsidies may be granted for crop digestion as compared to waste digestion. The main idea behind this strategy is that crops have to be purchased as substrates whereas gate fees are often received for waste material. Countries like Germany and Austria have lists of biogas feedstocks that are permitted for an extra subsidy in crop digestion. Although mixtures are permitted in some cases, the type of feedstock should generally fit to the corresponding subsidy scheme.

3.3 Essential laboratory analysis of feedstocks

The most important types of analysis for biogas feedstocks are now described. A summary of the different norms and standards for the analyses can be found in Section 3.7 at the end of this chapter.

3.3.1 Sample taking and preparation

For biogas feedstocks, standards VDI 4630 and ISO 566713 give detailed information on different issues relating to sampling. The quality of many feedstocks can differ depending on the time and sampling location. Especially for heterogeneous feedstocks, the sample taker's experience and knowledge of the overall process are of high importance. According to



3.3 Influence of different steps in the analysis of a feedstock sample on the total error (source: Schwedt G (2007) *Taschenatlas der Analytik*. Wiley-VCH, Weinheim, Germany; Figure A on p. 19; copyright Wiley-VCH Verlag GmbH & Co. KGaA; reproduced with permission).

VDI 4630, in order to obtain the best results, the rationale for and the methodology of sampling needs to be clarified in advance, to include

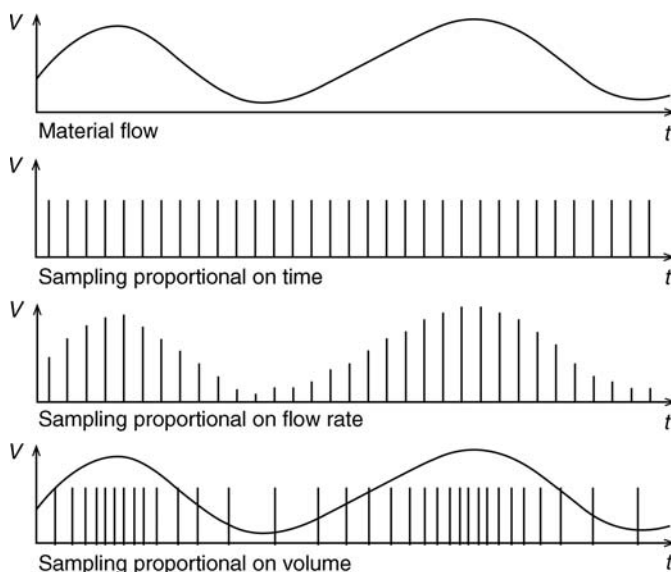
- the aim of investigation
- origin of material
- expected sample characteristics
- variation of sample characteristics with time and location of sample taking
- parameters to be analysed
- need for security and protection measures for sample taker.

Sampling procedure

A representative sampling procedure is essential for obtaining accurate data because many substrates are of inhomogeneous consistency. Therefore, to receive accurate data, a representative sampling procedure is a prerequisite. Details on sampling of biogas feedstocks in general can be found in VDI 4630 and details for sampling of sludges and wastewater are described in ISO 5667-13. Petersen (2005) gives a practical guide on sampling.

Figure 3.3 shows the influence of the different steps of an analysis on the accuracy of a result. It can be seen that the biggest error occurs during sample taking. The second biggest influence on error is sample treatment and preparation. The analysis itself normally causes the smallest error.

For homogeneous material, one sample is generally sufficient for a representative analysis. If the material shows very inhomogeneous phases, at



3.4 Sampling with different flow rates and material composition
 (source: Schwedt G (2007) *Taschenatlas der Analytik*. Wiley-VCH, Weinheim, Germany; Figure E on p.19; copyright Wiley-VCH Verlag GmbH & Co. KGaA; reproduced with permission).

least one sample should be drawn from every phase. These samples can then be mixed together according to the quantity of the phases. If the material is very inhomogeneous and no phases can be located, samples should be drawn from different locations and depths of the material. They can also be put together as a mixed sample.

For solid material, a representative sample can be obtained using the following procedure. With a spade or a sampling device, a large sample is taken from the material. This large sample is spread onto a clean surface and then mixed well. A cross is then drawn through the middle of the spread sample and two opposite quarters are removed. The remaining two quarters are spread and mixed again and again a cross is drawn and two quarters removed. This process is repeated until the required amount of sample is obtained.

For liquid material, the liquid has to be stirred well before sampling. The sample bottle should then be submersed into the liquid for sampling. If a sampling valve is used, the first material leaving the valve should be rejected to allow cleaning of the sampling valve. If a sample is taken from a pipe where the material passes at different flow rates and with different composition, a sample proportional to flow rate or volume can be taken (Fig. 3.4). Automatic sampling devices can be used for this purpose. In

addition, sampling in a pipe is preferably carried out in a vertical pipe or a pipe with turbulent flow so that problematic sediments can be avoided.

Sample transport and storage

Clean re-sealable sampling vials made of inert plastic, glass or steel should be used. After sampling, the vials have to be labelled. If poor biologic stability of the sample is assumed, samples must be cooled to 4°C during transport. All samples should be stored in a cooling chamber at 4°C until analysis. Obviously, short storage times before analysis are preferable to long storage times. If longer storage times are expected, samples can also be stored at -20°C, although this might produce changes in the degradability of the substrate.

Sample preparation

Physical impurities can be sorted out from the sample, but their amount and mass have to be documented. Samples are sometimes dried before analysis but this is only really suitable when non-volatile substances are being measured as it can cause the loss of some volatile components and therefore a false result. For some tests, milling or cutting the sample can improve analysis accuracy due to increased homogeneity of the sample, but milling of wet samples is often only possible after drying. An alternative way to mill organic fibres without drying (and without the associated losses) is during cooling with liquid nitrogen, but this is very rarely applied in the biogas field due to very high costs. Mixing in a blender is another alternative, although it is limited by high fibre content. Water can be added to the sample to improve blending performance.

3.3.2 pH value

The pH value determines the acidity or basicity of an aqueous solution. Its unit is the negative logarithm of the concentration of hydronium ions (H^+). The pH value can be determined in a liquid feedstock with a standard potentiometric electrode (standards EN 12176 and APHA 4500- H^+ B (see Section 3.7)). For semi-solid or solid feedstocks, the sample can be mixed with water and then analysed. Quite a wide range of pH values of biogas feedstocks is acceptable due to the usually high buffer capacity of the anaerobic digestion broth. The pH value in anaerobic fermentation is normally slightly above neutral. The buffer capacity depends mainly on CO_2 concentration in the gas phase, ammonia concentration in the liquid phase and water content in general. If the pH in the feedstock is too high or too low so that the buffer capacity is exceeded and the pH in the reactor is

changed significantly ($< \text{pH } 6.8$, $> \text{pH } 7.5$), it is preferable to have a neutralisation step before feeding to the biogas plant. If slight acidification occurs during anaerobic digestion, the pH can be increased artificially by adding base (e.g. $\text{Ca}(\text{OH})_2$, Na_2CO_3 , NaOH) in the reactor (Bischofsberger *et al.*, 2005).

3.3.3 Total solids (TS) and dry matter (DM)

For the estimation of the water content of a feedstock, the TS or the DM are determined. Both parameters represent the same and are described in units of percent or grammes per litre. This analysis involves drying the sample to constant weight in a drying chamber at $103\text{--}105^\circ\text{C}$ (standards EN 12880 and APHA 2540 B). A drawback of this determination is that volatile substances (e.g. volatile acids, alcohols) are not determined, although they can represent a considerable percentage of the energy in the feedstock. This difference is especially noticeable in wastewater and industrial by-products with high levels of volatiles.

If feedstocks have a very high TS content, the addition of fresh water or other liquid feedstocks to the biogas plant will be necessary. Alternatively, process liquids such as the digestate or the liquid fraction of digestate after solid–liquid separation can be used to dilute the feedstocks. If feedstocks with a very high water content are used (or a lot of fresh water is added to the process), the volume of digestate will be high and, consequently, its nutrient concentration will be low.

3.3.4 Volatile solids (VS) and organic dry matter (ODM)

In order to determine the amount of organic matter in a sample, the VS (%) or ODM (g/l) are determined. In general, this determination is carried out together with the TS/DM determination just described. The sample is dried to constant weight in a drying chamber at $103\text{--}105^\circ\text{C}$. Then the sample is ignited to constant weight in a muffle furnace at 550°C . (The relevant standards are EN 12879 and APHA 2540 E.)

Although this is a useful and simple analysis, it is important to take into account that the amount of organic matter in a sample does not directly give sufficient information on the anaerobic degradability of the feedstock. In addition, as mentioned above, VS/ODM determination can be inaccurate. Substances that are volatile at 103°C leave the sample during the first drying step.

3.3.5 Chemical oxygen demand (COD)

Chemical oxygen demand is a parameter that indicates the total chemically oxidisable material in the sample and therefore indicates the energy content of a feedstock. In this analysis the sample is refluxed in a boiling mixture of sulphuric acid and a known excess of potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$). A silver sulphate catalyst can be added for improved oxidation performance. Apart from that, mercury nitrate can be added to counteract the interference of chloride ions by forming complexes with them. As a next step, the remaining unreduced potassium dichromate is titrated with ferrous ammonium sulphate, which allows the determination of the consumed oxygen equivalents. (Standards DIN 38 414 and APHA 5220 B apply.)

The COD represents the maximum chemical energy present in the feedstock. Since microbes convert chemical energy to methane, this is also the maximum energy that can be recovered as biogas, though losses for the energy demand of the microbes themselves have to be subtracted, as well as for material that is not degradable by anaerobic microorganisms (e.g. lignocellulosic material). The main advantage of this method compared to the VS/ODM determination is that volatile components can also be determined provided that good cooling is applied and the condenser is working when adding sulphuric acid.

The COD analysis can give quite high errors due to sample inhomogeneity and the large number of sample treatment steps required (dilution, weighing and titration). It should therefore preferably be carried out by experienced personnel. For typical biogas feedstocks, which contain high concentrated organic matter and bulky material, drying and milling of samples can improve reproducibility. However, as mentioned earlier, a loss of volatile substances can occur. Raposo *et al.* (2008a) present a modified method for improving the COD determination of solid substrates and solutions with high suspended solid content. It is also important to be aware of the toxic components (potassium dichromate, mercury nitrate) that are used in COD measurements, as well as their proper disposal.

3.3.6 Nitrogen content

The nitrogen content of a feedstock can be determined by the total Kjeldahl nitrogen (TKN) determination (ISO 5663; ISO 11261; APHA 4500-N_{org} B). In this analysis, organic nitrogen is converted to ammonia nitrogen by boiling the feedstock sample in the presence of sulphuric acid and a catalyst. After that, a base is added and ammonia is distilled from the alkaline solution to an acid solution (usually boric acid) where ammonia is absorbed quantitatively. The amount of ammonia can then be determined by different methods, for example potentiometric acid titration or the photometric

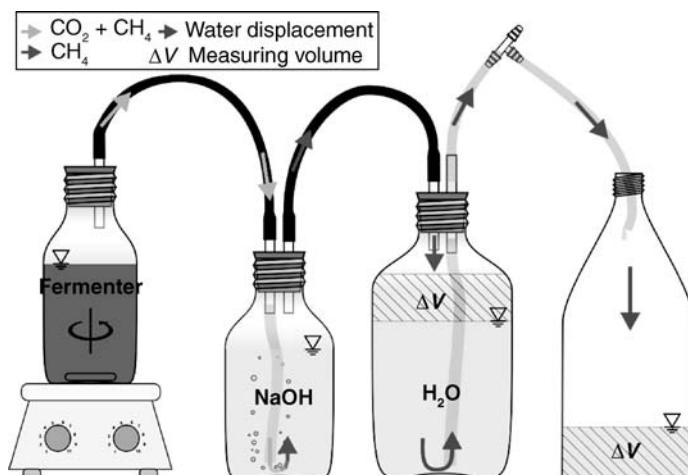
phenate method (ISO 5663 and APHA 4500-N_{org} B; see Section 3.7). The ammonia nitrogen (NH₄-N) determination is quite similar to the TKN determination but the first boiling step for organic nitrogen degradation is left out (DIN 38 406(E5); APHA 4500-NH₃).

Determination of TKN in a sample is important, primarily to evaluate if there is sufficient nitrogen available for the growth of anaerobic bacteria. In most cases there will be excessive nitrogen in the biogas reactor, so determination of the TKN content in a biogas feedstock helps to estimate nitrogen concentrations in the biogas reactor. As a rough estimation, it can be assumed that 60–80% of the TKN will be degraded to ammonia during anaerobic digestion, though deviations can occur depending on the specific substrate. This is important to know, because ammonia inhibition can occur if the ammonia concentration in the reactor exceeds certain levels. Details on recommended C:N ratios are described in Section 3.5.3 and details on ammonia inhibition can be found in Section 3.5.4. Biogas feedstocks with high nitrogen concentrations are generally protein-rich materials such as slaughterhouse waste, stillage, rape seed cake and residues from meat processing.

It should be noted though, that a TKN determination does not determine all nitrogen present. Substances such as nitrates or nitrites are not determined, but these substances occur mostly in negligible concentrations in biogas feedstocks. In most cases, the NH₄-N concentration of a biogas feedstock gives only limited information, since ammonia content rises strongly during anaerobic degradation of the proteins. However, the ratio of NH₄-N to TKN in a feedstock can provide information on the amount of available protein.

3.3.7 Biochemical methane potential (BMP)

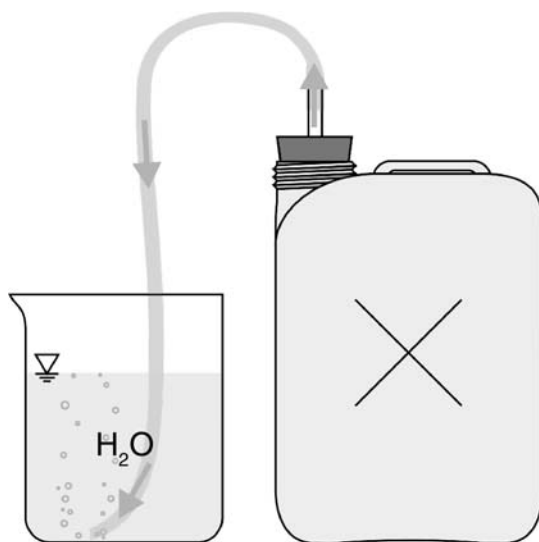
Biochemical methane potential tests are mainly used to determine the possible methane yield of a feedstock. These tests also provide information on the anaerobic degradability of a feedstock, including the degradation rate. In addition, a first rough evaluation of the presence of inhibitory components can be made. Standardised anaerobic degradation tests are given in EN 11734, DIN 38 414 (S8) and VDI 4630. The BMP test presented here is mainly based on DIN 38 414 (S8) and is slightly simplified according to Braun (1982, 2007). To make the test more practical, the expensive eudiometer gas measuring devices are replaced by simple water displacement bottles. In addition, a bottle with an alkaline solution is placed after the digester vessel in order to absorb the produced carbon dioxide and to allow direct methane measurement.



3.5 Simplified experimental set-up to determine BMP. Carbon dioxide in biogas is absorbed in an alkaline solution and the residual gas volume is measured by water displacement.

Experimental set-up of simplified BMP test

The set-up of the simplified BMP test is shown in Fig. 3.5. For every feedstock sample, a triplicate BMP test should be carried out. In addition, in every BMP test row, a triplicate of blanks (only inoculum) has to be set up. If BMP tests are carried out for various feedstock samples in one experiment, one blank triplicate is sufficient. To set up a BMP test, the feedstock sample and the inoculum (ratios are discussed later) are weighed and filled into a glass vessel of capacity 0.5–1.0 l. A magnetic stirrer is added for mixing and, if desired, the gas phase can be flushed with nitrogen before closing. Then the vessel is placed in a climate chamber or a water bath. To determine methane concentration without carbon dioxide, the digester vessel is connected to a bottle of alkaline solution (2–4 mol/l NaOH), which is then connected to the water displacement bottle (1–2 l). The water volume in the water displacement bottle has to be larger than the expected gas production volume. A tube leaves the displacement bottle to a recipient, where the daily production volume can be retrieved and measured. Initially, the volume should be read daily. After a decrease in gas production, the volume can be read two or three times per week. The majority of gas is normally produced during the first week. After 20–30 days the biological degradation is normally almost finished. The BMP tests can be stopped when daily gas production is lower than 1% of total gas production. At the end, a pH measurement of every BMP test should be carried out to check if acidification has occurred or if alkaline solution has been drawn back to the digester flask due to negative pressure. In either case, the BMP test will have to be repeated.



3.6 Correct storage of inoculum for BMP tests (in a temperature-controlled environment).

Inoculum

In standard BMP tests, anaerobically stabilised sewage sludge is used as inoculum (standards EN 11734 and DIN 38 414 (S8) apply). However, for special substrates such as crops, sludge from a crop digester could perform better due to adaptation to this substrate. It is important not to use sludge from instable biogas reactors as these are likely to contain inhibitors and microorganisms with reduced activity. If the sludge contains bigger particles, it should be sieved before utilisation. Apart from that, depending on the sludge type, the buffer capacity can be very limited. Consequently, sludges with a high buffer capacity are preferable, or buffer media can be added to the sludge. For a high-throughput laboratory it could be also attractive to operate a seed digester with an operational inoculum (EN 11734). In order to improve the set-up, EN 11734 recommends washing the inoculum material, centrifuging it and re-suspending it in a buffered medium. Trace element solutions may also be added to the sludge to counteract possible reduced activity due to trace element limitation.

Short-term storage of inoculum can be done at the appropriate temperature (mesophilic inoculum at 35–38°C) in a plastic canister that maintains anaerobic conditions but allows gas to escape (Fig. 3.6). Active inoculum can be stored for about a week before utilisation. If the inoculum has to be stored for a longer period, small amounts of degradable material can be added regularly to sustain the activity of the inoculum. However, long storage times are not preferable.

Substrate/inoculum ratio

The ratio of substrate to inoculum is an important factor in BMP tests, particularly in terms of degradable material (volatile solids) load in the sample and inoculum. According to VDI 4630, the ratio of VS_{sample} to VS_{sludge} should be ≤ 0.5 . If the amount of feedstock sample is very low, the effect of any occurring degradation in the inoculum sludge will be disproportional and can lead to errors. If the amount of feedstock sample is very high, there is a high probability of acidification. This occurs if the accumulation of acids in the hydrolytic phase exceeds buffer capacity, thereby lowering the pH in the test. This is a problem because little methanogenesis can take place below pH 6.5–6.0. However, a buffer solution can be added to decrease the probability of acidification (EN 11734; Raposo *et al.*, 2006). According to Raposo *et al.* (2006, 2008b), a considerable change in the ratio of substrate to inoculum can cause differences in the results. In addition, if water displacement bottles are used, the amount of sample should be adapted to the biogas measuring capacity of the water displacement bottles. If necessary, larger water displacement bottles can be used.

Gas measurement details and alternatives

For accurate results, the set-up (Fig. 3.5) should be tested for gas tightness before the experiments. To do this, the closed set-up can be run with a slight overpressure so that the water level rises some centimetres in the exit hose of the water displacement bottle. The water level can be marked and then checked after a few hours. If the water level stays near the mark, the set-up should be sufficiently gas tight. The effect of very small leaks can be amplified in set-ups that work under larger overpressure (e.g. water displacement or pressure measurement). Different methodologies are given for gas volume measurement. In EN 11734, gas production is calculated by measuring the build-up of overpressure in a closed set-up. In DIN 38 414 (S8), gas production is measured by water displacement in a eudiometer. Other viable options given in VDI 4630 are gas collector tubes, collection in gas bags or continuous gas measurements by micro gas counters or gas meters. In general, gas measuring methods such as water displacement and pressure measurement only allow limited total gas production. For continuous gas counters there are practically no limits, so decisive up-scaling of the BMP tests is also possible.

The set-up illustrated in Fig. 3.5 is designed only for methane measurement. If the biogas (including its other gases) is to be measured, the bottle containing the alkaline solution has to be removed from the set-

up. In addition, the water in the water displacement bottle should be acidified so that hardly any CO_2 will dissolve in it (DIN 38 414 (S8)).

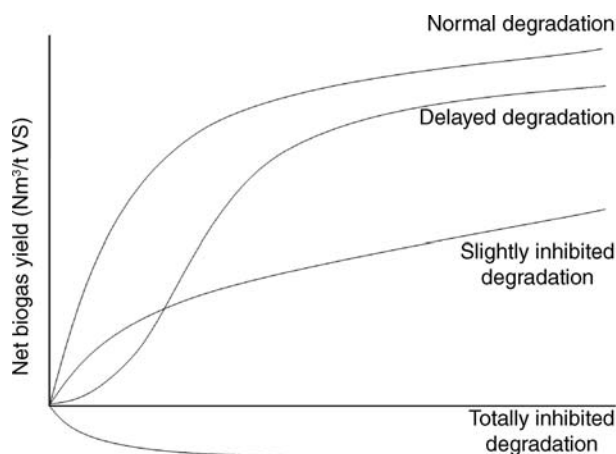
Evaluation of BMP test

Gas production of the blanks (i.e. batch trials with only inoculum and no substrate) should not exceed 20% of the total gas production in the BMP tests (VDI 4630). Otherwise, the results will have too much uncertainty. Daily gas production can be obtained by subtracting the gas production of the blanks from the daily gas production of the tests with samples. After that, based on the ideal gas equation (equation 3.1), the measured gas volumes have to be calculated at normal volumes ($T_0 = 273\text{K}$ and $p_0 = 1013\text{ hPa}$). Therefore, the ambient pressure (p) and the ambient temperature (T) – more precisely, the temperature of the gas in the displacement bottle – have to be known. For a more accurate calculation, the additional hydrostatic pressure of the displaced water (normally approximately 10 cm) will have to be added to the ambient pressure (p). On the other hand, the vapour pressure at ambient temperature can be subtracted from the ambient pressure (p).

$$V_0 = \frac{V \cdot p \cdot T_0}{p_0 \cdot T} \quad [3.1]$$

As a next step, depending on the daily gas production, a degradation curve can be drawn (Fig. 3.7). The degradation rate can be evaluated according to the steepness of the graph. Very steep curves mean very good availability and degradability, while flat curves mean slow feedstock availability or slight inhibition. If degradable organic matter is added and no (or negative) net biogas production occurs, this is a sign of very strong inhibition or toxicity of the feedstock. In reality, variations of these curves often occur. In general, it is preferable not to base the BMP on fresh weight because the water content of a feedstock can vary. For solid feedstock and feedstock with very limited volatile components, the BMP is often based on VS. For high-strength wastewater and feedstock with many volatile components, it is preferable to base the BMP on the COD. For comparison with other data, it is best to provide both.

Due to the complexity of this method of analysis and the many influencing factors, there is a strong possibility of error and inaccuracy. Apart from the representativity and inhomogeneity of the sample, the type and condition of the inoculum can have a very big influence on the results. Other influencing factors are the inoculum to substrate ratio, gas tightness of the whole set-up and the accuracy of VS or COD measurements. For a rough evaluation, the results can be compared to literature data. In



3.7 Examples of BMP degradation curves (adapted from VDI 4630 and DIN 38 414 (S8)).

addition, a BMP measurement should never exceed $350 \text{ Nm}^3/\text{t COD}_{\text{added}}$, which is the theoretical maximum according to Speece (1996). According to VDI 4630, the representativity of the results of BMP tests can be tested by using microcrystalline cellulose for reference samples.

3.4 Additional laboratory analysis of feedstocks

In addition to the essential feedstock analysis described in Section 3.3, extra analyses used in the field of biogas feedstock characterisation are now described. Depending on the specific situation, one analysis may be more appropriate than another. A summary of the different procedures for analysis can be found in Section 3.7.

3.4.1 Trace element analysis

The analysis of trace elements is described in EN 13346 (sludges) and ISO 11885 (wastewater), as well as in APHA 3120 C. For biogas feedstocks, drying and milling (e.g. ball mill) is recommended before analysis. The sample is then digested in a boiling *aqua regia* (EN 13346). If some indigestible solid particles remain, they should be removed by filtration. For subsequent elementary analysis, AAS (atomic absorption spectroscopy), ICP-OES (inductively coupled plasma – optical emission spectroscopy) or ICP-MS (inductively coupled plasma – mass spectroscopy) can be used. This analysis allows a very broad range of elements to be analysed; for details see EN 13346 and ISO 11885 (see Section 3.7).

The determination of trace elements can be useful if some trace elements

that are essential for anaerobic microbes are missing (or in very low concentrations). However, this analysis gives no direct information on the bioavailability of the trace elements. Lack of trace elements can often occur in monodigestion (e.g. maize, stillage). Trace element analysis also gives information on whether heavy metals exceed toxic concentrations in biogas feedstocks. Apart from that, this test can also assess nutrient content for the evaluation of digestate use as fertiliser.

3.4.2 Sulphur content

Total sulphur content can be determined according to ISO 11885 by ICP-OES. Biogas feedstock sample preparation is similar to trace element analysis (see Section 3.4.1). However, the wavelength of sulphur is very low compared with the other elements, which can sometimes produce problems in the accuracy of the detection.

Sulphur determination in biogas feedstocks is not always essential. However, high sulphur concentrations will lead to high H_2S concentrations in the biogas, which can lead to microbial inhibition and are of issue for end use of biogas in, for example, gas engines. If the feedstock has a high nitrogen content, the sulphur content of the feedstock should be analysed. The reason for this is that NH_3 and H_2S have synergistic negative effects (Chen *et al.*, 2008) and even a moderate sulphur content in biogas feedstocks can become problematic. Substrates that can be problematic due to high sulphur content are stillages or industrial wastewaters with high sulphate concentrations.

3.4.3 Phosphorous content

Total phosphorous content can be determined according to ISO 6878, DIN 38 414 (S12) and APHA 4500-P. As a first step, biogas feedstock samples are dried and milled. The sample is then digested in a mixture of sulphuric acid and nitric acid in order to solubilise all existing phosphorous. With addition of an acid complexing agent, the blue complex antimony phosphorous molybdate is formed, which can be measured quantitatively by photometric extinction measurements. An alternative way of determining total phosphorous is described in EN 13346 (sludges) and ISO 11885 (wastewater). After digestion of the sample, total phosphorous content can be analysed by AAS, ICP-OES or ICP-MS.

In most biogas feedstocks (e.g. crops or organic wastes), it can be assumed that sufficient phosphorous is available for microbial growth and this analysis is thus rarely carried out. However, phosphorous analysis of a feedstock can be a valuable indicator for the fertiliser value of the digestate after anaerobic digestion.

3.4.4 Total organic carbon (TOC)

The total carbon in a sample is made up of total inorganic carbon (TIC) (such as dissolved carbon dioxide, carbonate and bicarbonate) and total organic carbon (TOC) – organic matter that can either be dissolved or particulate matter. Consequently, TOC can either be determined by itself or by subtracting TIC from the total carbon. Standard procedures for TOC measurements can be found in EN 1484 or APHA 5310. For biogas feedstocks, sample preparation is important. Solid or practically solid substances are normally dried before TOC analysis. Lightly contaminated watery samples (without particulate matter) can be injected directly into a TOC analyser suitable for liquid samples. However, most biogas feedstocks that are not solid contain many particulates. Therefore, solid–liquid separation and separate analysis of the two phases can make sense. In practice, the drying of these liquid or semi-liquid samples will often be preferred.

For TOC analysis, the sample is acidified or purged with CO₂-free gas for TIC removal. The next step is oxidation of the TOC. The oxidation of medium- and high-TOC samples is often done by combustion; in liquid samples, chemical oxidation (often supported by UV photo-oxidation) is also applied. The produced CO₂ is quantified by infrared sensors or thermal conductivity sensors.

Although TOC gives exact information on the amount of organic carbon in a feedstock sample, it does not give any information on its biodegradability. Lignocellulose, for example, will be determined as TOC, yet it is not anaerobically degradable. In addition, the TOC does not give any information on the oxidation state of the carbon in the feedstock; a COD analysis provides better information in this regard. To sum up, although a TOC analysis of a biogas feedstock sample can give good information on carbon content, in practice a COD analysis is often preferred.

3.4.5 Continuous fermentation tests

The performance of a biogas feedstock under practical conditions can be influenced by various factors (Braun, 2007) – inadequate substrate concentration and nutrient composition, inhibiting substrate components, metabolite formation and inhibiting process operational conditions. Continuous fermentation tests give reliable information on the long-term performance of a substrate in a biogas reactor. However, these continuous tests are quite expensive due to their duration and the high amount of analysis involved.

Experimental reactor set-up

An example of a continuous biogas fermentation trial is illustrated in Fig. 3.8, which is a comparably simple set-up based on the BMP test (Fig. 3.5). The gas measuring device shown was designed and assembled in a laboratory setting, but there are different types of devices on the market (e.g. gas meters, micro gas counters). This set-up is only suitable for liquid substrates and substrates with small particles as feeding is done via a hose. In biogas research institutions, more sophisticated digesters that are especially designed for the needs of the biogas process are generally used. An example of a digester for solid substrates can be seen in Fig. 3.9.

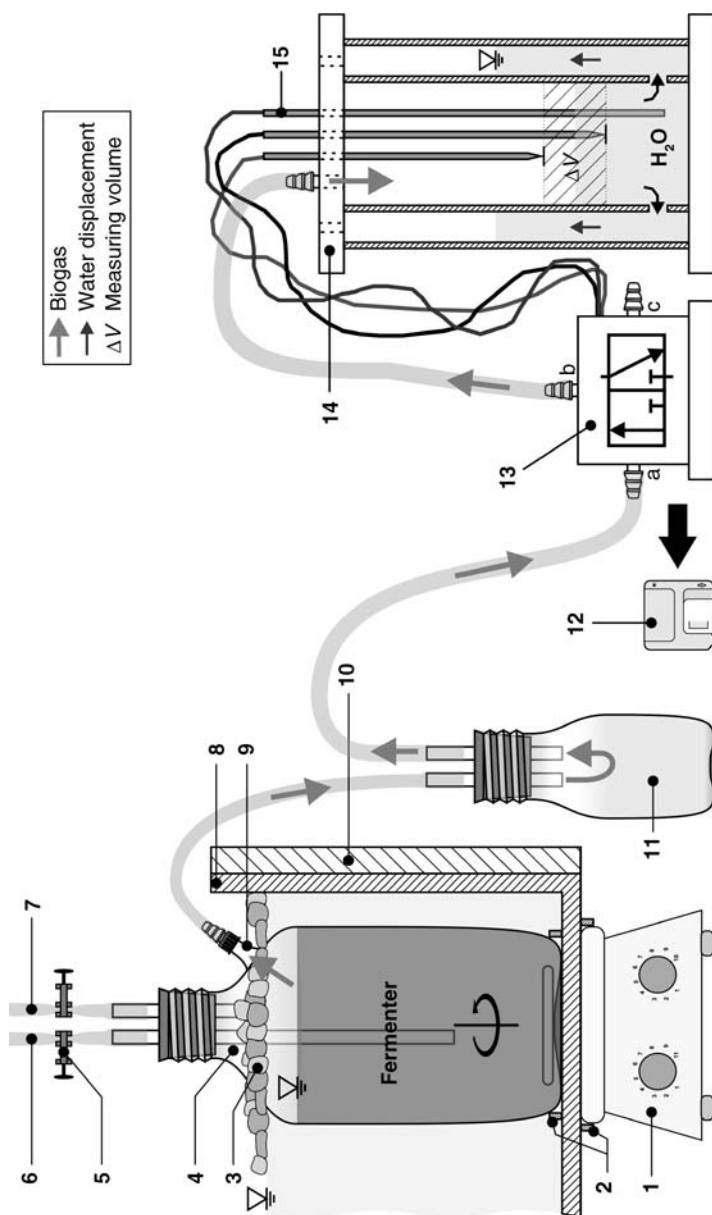
Experimental details for continuous biogas trials

The substrate used for the experiment should be characterised for pH, TS, VS, TKN and $\text{NH}_4\text{-N}$; COD determination is optional, depending on the substrate type. Sometimes, if the substrate is easily storable and a large cooling chamber is available, it is possible to use the same substrate batch throughout the whole experiment. Normally though, different substrate batches will be used during the experiment, so a representative sample of every substrate batch has to be taken.

Feeding of the digesters can be done manually (once or twice a day). However, feeding on weekends is often problematic, so feeding automation can be advantageous. Apart from that, the digester effluent has to be collected regularly, either automatically or by hand. Process monitoring includes the amount and composition of the biogas, fermentation temperature recorded online and pH, often measured offline. For a good measurement, the temperature of the sample during the pH measurement has to be recorded. Nevertheless, the pH may vary due to CO_2 degassing. Therefore, it is more accurate to measure the pH online; for this, a sophisticated pH adapter is necessary in which the electrode can be taken out for cleaning during a running fermentation. Effluent samples are taken regularly from the digester to determine TS, VS, TKN and $\text{NH}_4\text{-N}$. As with the substrate, COD determination is optional. Also, P and K can be analysed to estimate the fertiliser value of the digestate.

Start-up for continuous biogas trials

The start-up phase of an anaerobic digestion process, in other words the time needed to reach a stable process, can often be problematic and time consuming. A normal start-up can take 2–3 months, followed by 1–3 months of steady-state fermentation. A prolonged start-up period can be necessary if the microbes need to adapt to the substrate (e.g. a strong change



3.8 Set-up of laboratory reactors including gas measuring device (adapted from Woerl, 2007): 1, magnetic stirrer; 2, bottle/stirrer fixing; 3, evaporation protection; 4, 2 l glass bottle; 5, tube clamp; 6, effluent sampling tube; 7, feeding tube; 8, water bath; 9, gas outlet with screw cap and plastic hose connection; 10, heat insulation; 11, foam retention bottle; 12, electronic data entry unit; 13, 3/2-way valve (a, inlet; b, connection to volume measuring device; c, outlet/sampling of biogas); 14, volume measuring barrel; 15, measuring electrodes.

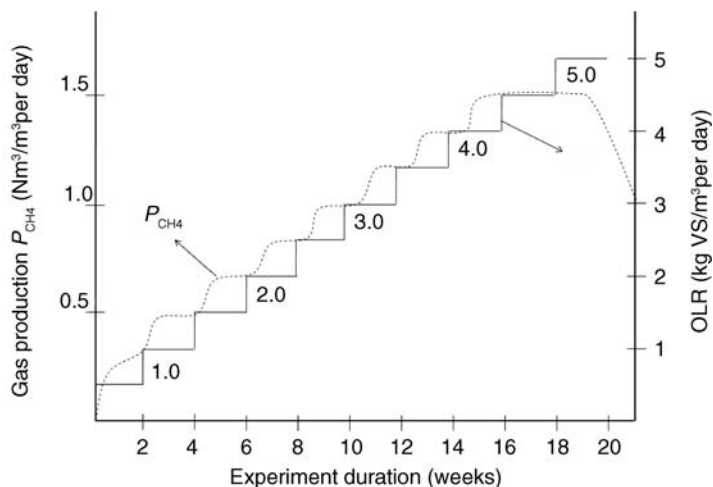


3.9 Laboratory digesters for solid substrate utilisation, showing two reactors with electric heat jackets, temperature control unit and stirring devices.

in substrate composition or the presence of inhibitors). Real representative conditions appear only after three volume changes (three retention times). In a CSTR (continuously stirred tank reactor), this means at least four months of operation (including start-up).

Standard VDI 4630 describe a simplified strategy for the fermentation start-up. The start-up should initiate at an organic loading rate (OLR) of $0.5 \text{ kg VS}/(\text{m}^3 \cdot \text{d})$. If the gas production is constant for 4 days, the OLR can be increased by $0.5 \text{ kg VS}/(\text{m}^3 \cdot \text{d})$. After that, the OLR can be increased by steps of $0.5 \text{ kg VS}/(\text{m}^3 \cdot \text{d})$ every 14 days until gas production declines (Fig. 3.10).

Start-up can also be carried out by adapting the feed of the reactors to the performance of the microbes. However, this requires experience and knowledge of the fermentation process, as well as a well-equipped laboratory. The reactor is started at an OLR of $0.5 \text{ kg VS}/(\text{m}^3 \cdot \text{d})$ and the following parameters are monitored: gas production (online), gas composition (two or three times per week) and volatile fatty acid (VFA) composition



3.10 Start-up scheme for continuous laboratory experiments, showing the daily gas production per m³ of reactor volume according to a rise in organic loading rate (OLR) (adapted from VDI 4630).

(once or twice per week). After every increase in OLR, the VFA concentration will rise and then decline again, which shows the adaptation. In the beginning, the OLR can often be increased faster than when coming near to maximum stable OLR. A sudden change in H₂ concentration, a sudden rise in total VFA or an increasing amount of propionic acid compared to acetic acid can indicate problems in microbial process stability. In response, the OLR should not be increased; it could even be slightly decreased. An absolute interruption of feeding for some days, however, can have negative impact on process stability, especially if the substrate is easily degradable. In addition, an experienced operator can give the microbes a period at low or medium OLR to adapt to a special substrate.

3.5 Detailed feedstock evaluation

3.5.1 Estimation of energy recovery potential

Estimation of the potential for energy recovery from a certain biogas feedstock can be carried out in different ways, some more accurate than others.

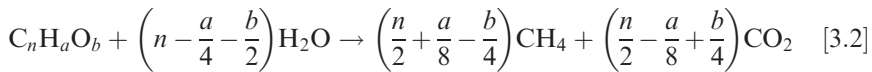
Literature data

The literature documents the biogas yields of different feedstocks; see, for example, Chapter 2 of this book. However, these data can vary considerably. To calculate the potential, it is generally better to consider

gas yields based on VS or COD rather than on fresh matter due to large variations in water content.

The Buswell formula

If the basic elementary formula ($C_nH_aO_b$) of the feedstock is known, a maximum biogas yield and methane content can be calculated according to the Buswell equation (equation 3.2) proposed by Buswell and Hatfield (1936). Using this formula, the theoretical uptake of water and the biogas amount and composition can be calculated. The results, however, only give a maximal biogas potential, and will often be much too optimistic since neither non-degradable material nor energy demand of the microbes are considered. A detailed example of how the Buswell formula can be used is described in Chapter 5 of this book.



Feed analysis

The content of lipids, proteins and carbohydrates of a biogas substrate can be determined using standardised animal feed analysis methods. Then, according to these feed components, the theoretical biogas yields and methane concentrations can be estimated (VDI 4630; Baserga, 1998; Bischofsberger *et al.*, 2005; Braun, 2007). An overview of the theoretical biogas yields and biogas composition is given in Table 3.1. The data in the table were calculated by inserting best estimates for the elementary composition into the Buswell equation (equation 3.2).

The calculation based on feed analysis gives only a rough estimate of the theoretical maximum biogas yield. However, real values will be much lower due to non-degradable material and energy demand of the microbes. According to VDI 4630, for fats and carbohydrates from animal origin, about 85% of the maximum biogas potential can be reached in practice; for fats and carbohydrates from plant origin, reaching 50–70% of the maximum is realistic. VDI 4630 also states that the methane content of biogas from proteins can reach up to 70%. In practice, a BMP test is often preferable to estimations based on feed analysis since it gives better information. However, in some cases, feed analysis data are already available so additional information on the maximal biogas recovery potential can be gained.

Table 3.1 Overview of theoretical biogas yield and biogas composition of carbohydrates, lipids and proteins

Substrate	Biogas yield (Nl/kg VS)	CH ₄ (%)	CO ₂ (%)	Elementary formula used for Buswell calculation
Carbohydrates	746	50	50	(CH ₂ O) _n ^a
Lipids	1390	72	28	C ₁₆ H ₃₂ O ₂ ^b
Proteins	800	60	40	C ₁₃ H ₂₅ O ₇ (N ₃ S) ^c

^a The elementary formula for soluble sugars (e.g. glucose) was used according to VDI 4630. However, it would be more realistic to use the elementary formula for starch/cellulose (C₆H₁₀O₅)_n, since most of the carbohydrates appear as chains (subtracting one water molecule) in biomass. This would give 830 Nl/kg VS. However, since these theoretical values are never reached in reality, it makes little difference.

^b The elementary formula of palmitic acid was used as an estimate for lipid elementary formula.

^c A best estimate for proteins according to the amino acid composition is used. However, the elementary formula of proteins can vary considerably.

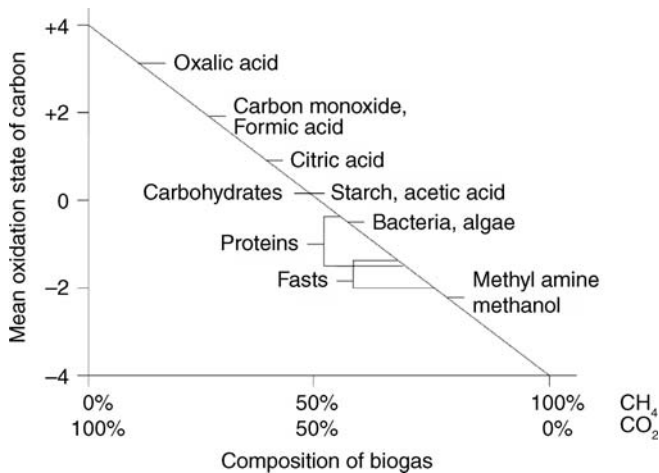
Source: Adapted from VDI 4630.

COD balance

By measuring the COD content of a feedstock, the chemically oxidisable material can be determined. This amount of energy is the absolute maximum of energy that could be recovered by biogas. However, under chemical conditions, some substances can be oxidised that are not accessible under biological conditions and will therefore remain in the digestate. Using continuous fermentation trials (see Section 3.4.5), the residual COD in the effluent of a stable process can be measured and therefore the exact COD degradation determined (corresponding to a specific OLR). For easily available feedstocks such as high-strength wastewater and industrial by-products, a COD degradation of 75–85% can be assumed. According to Speece (1996), 1 kg of degraded COD will produce 350 Nl of methane. Consequently, for a COD degradation of 80%, the methane yield will be 280 Nl methane/kg COD_{Input}.

BMP test

A very practical way of determining the potential for energy recovery is to measure the BMP (see Section 3.3.7). This gives a quite realistic result for the expected methane potential. Although this approach is generally the best option and much more accurate than the options already described, it has some drawbacks. For example, the methane potential will change depending on the OLR applied in a continuous fermentation process. Possible inhibitors are diluted by the inoculum added in the BMP tests and the synergistic or antagonistic effect of substrate mixtures can only be evaluated



3.11 Influence of oxidation state on gas composition (adapted from Speece, 1996).

to a very limited extent. Furthermore, a BMP test is quite complex and errors can occur quite easily, as explained in Section 3.3.7.

Continuous tests

The most accurate data on biogas production from a feedstock or feedstock mixture can be obtained from continuous fermentation tests (see Section 3.4.5). However, these tests are rarely done for the sole purpose of estimating the energy recovery potential due to the very great effort and costs involved.

3.5.2 Influence of carbon oxidation state on methane concentration

The methane concentration in biogas can be estimated using the Buswell formula or according to feed analysis. The relationship between carbon dioxide and methane in biogas depends on the mean oxidation state of carbon in the feedstock. Figure 3.11 gives a good overview of the mean oxidation state of different substrates and the corresponding CO₂ and CH₄ concentrations.

Carbohydrates show CH₄ concentrations of about 50%, proteins in the range of 55–70% and fats between 70 and 75%. The feed that actually goes into biogas plants is more likely to be a mixture of these components. Therefore, in most biogas plants, the CH₄ concentration of biogas lies between 50 and 60%. In addition, it should be mentioned that some of the

CO₂ leaves the biogas plant via the digestate (buffer capacity). A high pH will even increase CO₂ solubility. This can have an influence on the CH₄ concentration in the measured biogas. Last but not least, non-degradable organic components cause large deviations from the theoretical oxidation state in many biomass feedstocks.

3.5.3 Nutrient demand and availability

Macronutrients

The composition of anaerobic microbial biomass can be estimated as 50% C, 20% O, 10% H, 11% N, 2% P and 1% S. In a biogas feedstock, the minimal demand for macronutrients in anaerobic digestion should be 1000:5:1:1 (COD_{degradable}:N:P:S) if the substrate is easily available for methanogens. If large amounts of the feedstock still have to be broken down by hydrolytic microbes, the demand for macronutrients rises to 350:5:1:1 (COD_{degradable}:N:P:S) (Bischofsberger *et al.*, 2005).

According to Braun (1982), the C:N ratios in biogas feedstocks (or feedstock mixtures) should range between 16:1 and 45:1. Bischofsberger *et al.* (2005) give a comparable range of C:N ratios for waste digestion 10:1 to 45:1 for the hydrolysis step and 20:1 to 30:1 for the methanogenesis step. However, according to Braun (1982): experiments with a very low C:N ratio of 4.2:1 (and a consequently large excess of nitrogen) have also been carried out successfully. Experiences of the current authors showed the same, but attention should be drawn to possible difficulties of process stability at high ammonia concentrations (see Section 3.5.4).

In general, it can be assumed that in most biogas feedstocks there is sufficient nitrogen and phosphorous available. Limitations of macronutrients (P, N) occur especially in monodigestion (e.g. industrial wastewaters). As countermeasures, macroelements will have to be added to these feedstocks, or else they will need to be co-digested with N- or P-rich feedstocks.

Micronutrients

The microbes in anaerobic digestion require certain micronutrients. According to Bischofsberger *et al.* (2005), the essential trace elements are Ni, Co, Mo, Fe, Se and Wo for methanogenic bacteria and Zn, Cu and Mn for hydrolytic bacteria. In co-digestion of various biogas feedstocks, sufficient micronutrients are often available. This is especially true if manure is among the substrates. In monodigestion, where only one type of substrate is used, the probability of trace element limitation is higher. While the trace element content of substrates can be analysed quite easily (see Section 3.4.1), the bioavailability of these trace elements is very difficult to

determine. An exacerbating factor is the precipitation of many trace elements by hydrogen sulphide. Speece (1996) describes simple tests for trace element limitation. If trace element limitation occurs in a biogas process, trace element solution will often have to be added.

3.5.4 Inhibition and toxicity by feedstock components

Some substances in biogas feedstocks can inhibit or be toxic to anaerobic microbes. Inhibition means a decrease or cessation of growth, whereas toxicity provokes death of microbes. It is important to know if inhibitory or toxic substances are present in biogas feedstocks. It is possible to adapt the microbial consortium to inhibitory substances. In the following text only a short overview of the most important inhibitory substances is given; for further details on inhibition see the works of Chen *et al.* (2008), Bischofsberger *et al.* (2005), Gerardi (2003), Speece (1996) and Braun (1982).

Ammonia inhibition

Ammonia is produced in anaerobic digestion from nitrogen-rich substrates. It is known that the undissociated form of ammonia nitrogen, $\text{NH}_{3(\text{aq})}$, is the inhibitory component in nitrogen-rich biogas fermentations. The concentration of $\text{NH}_{3(\text{aq})}$ depends strongly on temperature and pH. In different literature sources, different inhibitory concentrations are given. According to Bischofsberger *et al.* (2005), inhibition starts at 1.5 to 3.0 g $\text{NH}_4\text{-N/l}$. However, there are reports that substantially higher concentrations could be tolerated without a decrease in degradation performance: 5.0 g $\text{NH}_4\text{-N/l}$ (Braun, 1982) and 8.5 g $\text{NH}_4\text{-N/l}$ (Speece, 1996). Comparable results have been obtained by the authors of this chapter. Chen *et al.* (2008) give an even broader range of concentrations at which about 50% reduction of methane production occurred: 1.4 to 14 g $\text{NH}_4\text{-N/l}$. In addition to the influence of temperature and pH on ammonia inhibition, the adaptation of microbes to high ammonia concentrations is also an important factor. In practice, high nitrogen feedstocks frequently pose problems on process stability in biogas plants. Rapid changes from low-nitrogen feedstocks to high-nitrogen feedstocks can be especially problematic. For a stable anaerobic process at high ammonia concentrations, the following parameters are a prerequisite: good adaptation of the microbes, good trace element availability and low to medium hydrogen sulphide concentrations.

Hydrogen sulphide inhibition

Hydrogen sulphide is produced by the anaerobic degradation of sulphur components. As with ammonia, the undissociated form, $\text{H}_2\text{S}_{(\text{aq})}$ is known to

be inhibitory. In addition, S^{2-} is known to precipitate many metal ions which can have a negative effect on the bioavailability of trace elements. According to Bischofsberger *et al.* (2005), inhibition starts at about 30 mg H_2S/l , whereas Braun (1982) states that inhibition does not normally occur below 100 mg H_2S/L and even 200 mg H_2S/l can be tolerated after sufficient adaptation time. According to Chen *et al.* (2008), the range of inhibitory thresholds for undissociated H_2S in literature is even broader: 40 to 400 mg H_2S/l . The range Speece (1996) reports, where about 50% inhibition occurred, is 60 to 240 mg H_2S/l . However, practical experience showed that H_2S can become problematic at much lower concentrations, especially when coupled with other inhibitory components such as ammonia (Chen *et al.*, 2008) or low iron concentrations.

Light and heavy metal ions

In low to medium concentrations, many light metal ions show no inhibitory effect on anaerobic digestion. According to Chen *et al.* (2008), the ions Na, K, Mg, Ca and Al can become inhibitory at very high concentrations. For Na, for example, the inhibitory concentration is 5.0 g/l although, after adaptation, concentrations up to 15 g/l were tolerated (Speece, 1996).

With regard to heavy metals, the situation is similar to other biological organisms – at low concentrations they can be essential for microbial wellbeing and at higher concentrations they can be toxic. In practice, heavy metals will be tolerated quite well due to the fact that they form poorly soluble precipitants with sulphide and carbonate. The lowest thresholds of reported negative effect are Cu (40 mg/l), Cd (20 mg/l), Zn (150 mg/l), Ni (10 mg/l), Pb (340 mg/l) and Cr (100 mg/l), according to Bischofsberger *et al.* (2005). Braun (1982) found the following concentrations to cause 20% inhibition at pH 8: Cd (157 mg/l), Ni (73 mg/l), Cu (113 mg/l) and Zn (116 mg/l). Most light and heavy metals can be detected using standard trace element analysis (see Section 3.4.1).

Antibiotics and disinfectants

It is obvious that most detergents and chemicals that are designed to inhibit or kill microbes will have a negative effect on anaerobic digestion. Antibiotics can be present in manure or other animal residues, whereas disinfectants can be part of wastewater from, for example, the food industry. These substances should be avoided in biogas feedstocks, although small amounts may be tolerated.

3.6 Conclusions

The abundance and variety of possible feedstocks for biogas production demonstrates that there is a need for detailed characterisation and evaluation of each specific feedstock type. For first estimates as to whether a feedstock is suitable or not, a principle understanding of the anaerobic digestion process is necessary. Typical biogas feedstocks should be degradable and have a considerable water content, but the amount of fibrous material (e.g. lignocellulosic material) should be rather low. If process production data of the feedstock are available, they can be used for a first evaluation of the feedstock. However, in most cases detailed laboratory analysis will be necessary. Essential analysis includes the determination of pH, total solids/dry matter, volatile solids/organic dry matter, chemical oxygen demand, total Kjeldahl nitrogen, ammonia nitrogen and biochemical methane potential. In many cases it will be sufficient to determine either the VS or the COD for the estimation of the energy content of a feedstock. The BMP test is the core analysis method for biogas feedstock characterisation. However, it can show a high level of uncertainty, and is much less informative than continuous fermentation trials. Such continuous fermentation trials give the best information on the performance of a biogas feedstock in a biogas plant. A big disadvantage, however, is that they are quite expensive due to the large amount of analysis required and the duration of the experiment.

To evaluate limitation by macroelements, the presence of nitrogen, sulphur and phosphorous can be determined. In practice, most biogas feedstocks provide sufficient macroelements because of the low demand of anaerobic microbes (compared with aerobic microbes). However, a lack of microelements (trace elements) can occur, especially in monodigestion. Classic trace element analysis (e.g. ICP-OES) can give valuable information on the concentration of these elements in a feedstock, but no information on the bioavailability of these elements. Nitrogen and sulphur analysis will provide information on possible ammonia and hydrogen sulphide inhibition.

The most important step in feedstock characterisation is to combine the information from the different analyses in order to obtain an overall picture on the suitability of a certain feedstock (or feedstock mixture) for a biogas plant. In total, process stability issues (inhibition, toxicity), fertiliser value of the digestate and the overall economics of a biogas project have to be evaluated. In short, reliable feedstock analyses and characterisation will always play a very important role in the biogas business.

3.7 Sources of further information and advice

Normatives and operating procedures are very important sources of information for carrying out biogas feedstock analysis. Table 3.2 gives a concise overview of the relevant standards and methods.

Table 3.2 Overview of relevant methods of analysis for the characterisation of biogas feedstocks

Analysis	Standard	Title
Sample taking	VDI 4630	Fermentation of organic materials – Characterisation of the substrate, sampling, collection of material data, fermentation tests
	ISO 5667–13	Water quality – sampling – Part 13: Guidance on sampling of sludges from sewage and water treatment works
pH value	EN 12176	Characterisation of sludge – Determination of pH value
TS/DM	APHA 4500-H+ B	pH value Electrometric method
	EN 12880	Characterisation of sludges – Determination of dry residue and water content
VS/ODM	APHA 2540 B	Total solids dried at 103–105°C
	EN 12879	Characterisation of sludges – Determination of the loss on ignition of dry mass
COD	APHA 2540 E	Fixed and volatile solids ignited at 550°C
	DIN 38 414 (S9)	German standard methods for the examination of water, wastewater and sludge; sludge and sediments (group S); determination of the chemical oxygen demand (COD) (S9)
	APHA 5220 B	Chemical oxygen demand (COD) – Open reflux method
TKN	ISO 5663	Water quality – Determination of Kjeldahl Nitrogen – method after mineralisation with selenium
	ISO 11261	Soil quality – Determination of total nitrogen – Modified Kjeldahl method
	APHA 4500–N _{org} B	Nitrogen (organic) – Macro-Kjeldahl method
NH ₄ –N	DIN 38 406 (E5)	German standard methods for the examination of water, wastewater and sludge; cations (group E) determination of ammonia–nitrogen (E5)
	APHA 4500–NH ₃ B	Nitrogen (ammonia) – Preliminary distillation step
	APHA 4500–NH ₃ C	Nitrogen (ammonia) – Titrimetric method
	APHA 4500–NH ₃ F	Nitrogen (ammonia) – Phenate method
S	ISO 11885	Water quality – Determination of 33 elements by inductively coupled plasma atomic emission spectroscopy
P	EN 13346	Characterisation of sludges – Determination of trace elements and phosphorous – Aqua regia extraction methods
	DIN 38 414 (S12)	German standard methods for the examination of

Table 3.2 (Continued)

Analysis	Standard	Title
		water, wastewater and sludge; sludge and sediments (group S); determination of phosphorous in sludges and sediments (S12)
	ISO 6878	Water quality – Determination of phosphorous, ammonium molybdate spectrometric method
	APHA 4500–P B	Phosphorous – Sample preparation
	APHA 4500–P E	Phosphorous – Ascorbic acid method
Trace elements	ISO 11885	Water quality – Determination of 33 elements by inductively coupled plasma atomic emission spectroscopy
	EN 13346	Characterisation of sludges – Determination of trace elements and phosphorous – Aqua regia extraction methods
	APHA 3120 C	Metals by plasma emission spectroscopy – Inductively coupled plasma (ICP) method
BMP	EN 11734	Water quality – Evaluation of the ultimate anaerobic degradability of organic compounds in digested sludge – method by measurement of the biogas production
	DIN 38 414 (S8)	German standard methods for the examination of water, wastewater and sludge; sludge and sediments (group S); determination of the amenability to anaerobic digestion (S8)
	VDI 4630	Fermentation of organic materials – Characterisation of the substrate, sampling, collection of material data, fermentation tests
TOC	EN 1484	Water analysis – guidelines for the determination of total organic carbon (TOC) and dissolved organic carbon (DOC)
	APHA 5310	Total organic carbon (TOC)

VDI, Verein Deutscher Ingenieure, Düsseldorf, Germany.

ISO, International Organization for Standardization, Geneva, Switzerland.

EN, European Committee for Standardisation, Brussels, Belgium.

APHA, American Public Health Association, Washington DC, USA.

DIN, Deutsches Institut für Normung e. V., Berlin, Germany.

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Storage and pre-treatment of substrates for biogas production

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Abstract: Biogas substrates are typically moist, which can make them difficult to store because bacteria and mould can grow on them. Ensiling, which involves the production of acid by lactic acid bacteria, is often used to preserve crops cheaply. Biogas substrates are also often fibrous, which can make them difficult to mix and means that some of their energy is locked up within the fibres. Different pre-treatment technologies are being investigated to access the energy in these fibres, to increase the rate of biogas production and to improve the mixing qualities of the substrates. Pre-treatment technologies are based on three principles: physical (including mechanical shear, heat, pressure and electric fields), chemical (acids, bases and solvents) and biological (microbial and enzymatic). Combinations of these principles are also used, including steam explosion, extrusion and thermo-chemical processes. Although many of these processes have been investigated at small scale, few have been analysed at large scale in un-biased studies. Many of these techniques are associated with high energy input (e.g. mechanical and heat pre-treatment), high equipment costs (e.g. mechanical systems where the blades erode) or use large volumes of chemicals (e.g. alkali pre-treatment). Different pre-treatment technologies work better with different substrates, and more research is required in this field to understand which combinations are worthwhile. This chapter describes some of the common pre-treatment technologies along with some advantages and disadvantages.

Key words: biogas, anaerobic digestion, pre-treatment, ensiling, anaerobic digestion analysis.

4.1 Introduction

Anaerobic digestion is a versatile process owing to the wide range of input materials that can be used as well as the various utilisation options for the gas produced and the digestate accumulated. A wide range of industrial residues, agricultural residues and energy crops are used and this versatility is the main strength of anaerobic digestion. However, there are two main difficulties that arise from this diversity – storage and processing.

Storage is an issue because many of the feedstocks accumulate seasonally, such as annual plants or wastes from campaign manufacturing processes, but need to be stored cheaply for the whole year. Because all the substrates contain organic matter and most are wet or moist, there is a high risk of microbial decay. This not only causes substrate loss, but can lead to strong odour emissions, and the toxins and spores formed can pose a risk to workers. To cope with this variety of input materials and the problems associated with them, different storage and stabilisation options have been developed. Ensiling is by far the most common storage strategy for agricultural raw materials, and is described in the next section.

Processing is an issue because substrates can be in many forms, from liquids and pastes to slurries and solids, with fibrous or granular particles. Viscous or fibrous materials are particularly hard to move and mix. In addition, the lignocellulosic complexes present in the fibres of many biogas substrates are recalcitrant to degradation. Different pre-treatment technologies have been developed in recent years to make lignocellulosic materials more available for degradation and to improve the viscosity and flow behaviour of substrates. The motivation behind these developments was to increase gas yield, enhance process stability and speed up the degradation rate. Pre-treatment technologies can be divided into physical, biochemical and chemical principles, but combinations of these are also used. This chapter gives an overview of the ensiling process and pre-treatment technologies for input substrates for biogas plants.

4.2 Storage and ensiling of crops for biogas production

Silage making, or ensiling, is not usually referred to as a pre-treatment step, but can be considered as one because it changes the properties of the substrate and adds a unit operation to the process. Ensiling is the preservation of crops, typically whole-crop cereals, grasses and legumes, by fermentation with lactic acid bacteria (LAB). The product, silage, is primarily used as a feed for ruminant livestock during winter months and also as a year-round feedstock for anaerobic digestion. This is particularly important because energy demands are higher in the winter when there is a lack of fresh crops (Seppälä *et al.*, 2008).

4.2.1 Mechanism

A variety of microorganisms are present on harvested crops, including some that can be harmful such as clostridia, coliforms and mycotoxin-producing fungi. These can grow on inappropriately stored crops and cause loss of substrate as well as disease in livestock and farm workers. LAB are also present on harvested crops and produce acids (mainly lactic acid) from sugars available in the plants. In contrast to hay production, in which the growth of all microorganisms is prevented by removing water, ensiling aims to promote the growth of these LAB and inhibit the growth of harmful microorganisms. This is done by storing the moist crops in a closed airtight system, where the oxygen is quickly used up by the plant's respiratory enzymes. The resulting absence of oxygen inhibits the growth of aerobic microorganisms including aerobic fungi. LAB are very tolerant to low water conditions so, by using a relatively dry crop, such as maize or wilted grass, or by using additives, LAB can grow faster than other, undesirable anaerobic bacteria. The acids produced by LAB cause a drop in pH and most undesirable microbial growth is inhibited (Wilkinson, 2005; McDonald *et al.*, 1991).

4.2.2 Production

A range of equipment can be used for producing silage, from expensive and very effective to cheaper and less reliable. Concrete tower silos are a more expensive option, but the vessel can be well sealed from oxygen (McDonald *et al.*, 1991). Walled bunker silos are less expensive but also a good option for keeping oxygen out. Considerably cheaper options include holes in the ground and silage heaps, which can be sealed with sand, biogas digestate or polyethylene sheets weighed down with, for example, rubber tyres. A large proportion (probably 25%) of silage in Europe is made using big bales, facilitated by the introduction of baler-wrapper machines (Wilkinson, 2005). Baled silage is particularly good for grasses and legume crops due to the method of harvest and the shape and structure of the harvested crop.

The three most important crop parameters in ensiling are: dry matter (DM) content, the amount of fermentable sugar available (water-soluble carbohydrate, WSC) and buffering capacity (Wilkinson, 2005). The right DM content is essential, as water is necessary for the growth of LAB, but too much moisture allows the growth of undesirable bacteria before the LAB have reduced the pH. Maize has a high DM content, which makes it particularly easy to ensile. Although grass has a lower DM content, it is also commonly ensiled. The ensiling of grass can be aided by cutting the grass on a dry day and leaving on the field after cutting, allowing water to evaporate from the plant and thereby increasing the DM content. This is known as

wilting and is typically carried out for one or two days. Wilting for more than 48 hours, however, can lead to WSC losses and mould development. Field wilting is not always possible owing to weather conditions, but ensiling of unwilted wet crops can be carried out by an experienced worker or improved by using additives such as acids to bring about a more rapid pH drop, starter cultures to give the LAB a head start or preservatives such as nitrite to inhibit unwanted microorganisms (Wilkinson, 2005; McDonald *et al.*, 1991).

Sugar concentration is also essential, as the production of acids during fermentation is dependent on sugar. The major WSCs of grasses are glucose, fructose, sucrose and fructans, and a WSC concentration below 30 g per kilogramme of fresh crop weight results in poor fermentation (Wilkinson, 2005). For whole-crop maize silage, WSC is not an issue as sugar is released from the corn grains, but in some grass species the WSC concentration can be very low, particularly when cut late in the season. The concentration of WSC is higher when grass is harvested in the afternoon (Nizami *et al.*, 2009). Wilting (for less than 48 hours) can be used to increase the sugar concentration as it removes water by evaporation. More carbohydrate is available in the plant material, but as cellulose, hemicelluloses and pectin, which cannot be used by LAB. Sugar may be released from these structural carbohydrates by using hydrolytic enzyme additives. An alternative commonly used additive for crops with low WSC is molasses (Wilkinson, 2005; McDonald *et al.*, 1991).

The buffering capacity of plants is also important and is affected by the number of weak acid salts such as citrate present in the plant material, which can recombine with the H^+ formed by the fermentation. This varies between crop types, but is often lower in mature crops. The presence of ammonia in the plant also has a buffering effect, as ammonia mops up the H^+ ions to form ammonium. Ammonia concentration in the plant is related to the use of fertiliser and can be reduced if fertiliser is applied early in the season and there is a long wait before harvest. Acid additives can be used to help ensiling of crops with high buffering capacities (Wilkinson, 2005).

4.2.3 Relevance for biogas production

Many different crops can be ensiled, but the most relevant for biogas production are whole-crop maize and grass, which make up 48% and 4% respectively of the fresh weight of biomass used for anaerobic digesters in Germany, the biggest biogas producer in Europe. In addition, over 90% of biogas plants in Germany use maize silage to some extent and over 35% use grass silage (Gemmeke *et al.*, 2009). Grass silage is expected to be of increasing importance for biogas production in Europe owing to the abundance of grasslands and the controversy of using arable land for energy

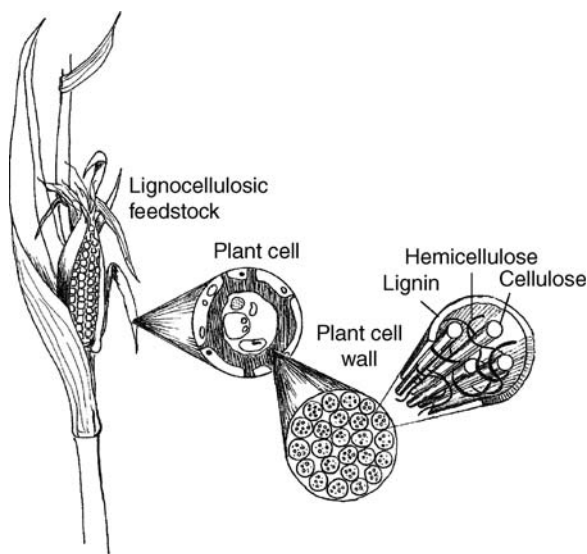
rather than food crops (Murphy and Power, 2009). What is referred to as grass is typically a mix of grass varieties and clover from grasslands. Other ensiled crops relevant for biogas production include other cereals such as sorghum and barley, as well as sugar beet tops, although a much wider range of materials can be stored in this way and used for biogas production, for example hemp (Pakarinen *et al.*, 2011), pineapple processing waste (Rani and Nand, 2004), mango peel (Madhukara *et al.*, 1993) and green pea shells (Madhukara *et al.*, 1997).

There have been several studies evaluating ensiling as a storage method for biogas substrates, particularly grass. These show that well-preserved silage has a relatively constant methane yield, even after months of storage (e.g. grass (Pakarinen *et al.*, 2008; Seppälä *et al.*, 2008) and cereals (Herrmann *et al.*, 2011)). Ensiling of maize or hemp has been shown to increase the available sugars and the amount of biogas produced (Pakarinen *et al.*, 2011; Amon *et al.*, 2007), and this is particularly true when acid was used as an additive (Pakarinen *et al.*, 2011). This is presumably because acid addition means fewer WSCs are used up by LAB and because the acidic conditions break down hemicelluloses. It also has been shown that some biological additives increase methane yield in maize silage (Vervaeren *et al.*, 2010), but also that some have no significant effect on methane yield from grass silage (Pakarinen *et al.*, 2008).

4.3 Pre-treatment technologies for biogas production

Anaerobic digestion is a well-established process for energy production. The fermentation takes place in four steps associated with different microbial populations: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The time needed for the degradation of biomass to biogas, or macromolecules to mainly methane and carbon dioxide, varies depending on the nature of the chemical bonding of the carbohydrate in the biomass (Noike *et al.*, 1985). The microorganisms in anaerobic digestion convert simple molecules, including sugars such as glucose, into biogas (see Chapter 5 for a more detailed description). Starch and cellulose are both chains of glucose units, but while starch is used by the plants as an energy store and is therefore easy to break down, cellulose is used to maintain the structure of the plant and is, by necessity, difficult to break down. The breakdown of cellulose is further complicated by the bonds between different cellulose chains, and between cellulose and hemicelluloses and lignin (see Figure 4.1). Converting this lignocellulose complex to sugar is the key to biofuel production, whether that is biogas or bioethanol.

Different pre-treatment technologies have been developed in recent years to increase the availability of carbon, particularly in lignocellulolytic material, for anaerobic digestion. Many of these technologies come from the



4.1 Lignocellulose complex in plant cell walls (courtesy of Lydia Rachbauer).

wastewater or bioethanol industries. There are a huge number of pre-treatment technologies and it is often difficult to assess which ones are worthwhile. Claims by manufacturers about the abilities of their technologies must be viewed with caution, as they often neglect to mention the disadvantages. Research carried out on behalf of these companies may also be misleading. Even other research is not always neutral, as every researcher has a specialist area and a preferred technology. It is difficult to draw a conclusion from the vast amount of studies published using different pre-treatment methods on different substrates. This is partly because costs are rarely considered in research papers. In addition, technologies that look promising at small scale in batch fermentation may not be effective at large scale in continuous fermentation. Different technologies and the positive and negative aspects of the technologies are now discussed.

4.3.1 Physical pre-treatment

Mechanical pre-treatment

Mechanical pre-treatment is a simple form of pre-treatment aimed at increasing the specific surface area and availability of biomass. In addition to increasing biogas yield, particle size reduction also has an effect on the viscosity in digesters and reduces the formation of floating layers that cause

problems in biogas reactors because they block outlets, are unavailable for digestion and interfere with gas escape (Kamarad *et al.*, 2010).

Different kinds of mills have been tested in the past, mainly hammer mills (crushing) and knife mills (chopping). Mechanical pre-treatment is one of the most expensive steps in biomass conversion because, although increasing specific surface area increases the biogas yield, electrical energy demand is very high. A particle size of 1–2 mm is recommended for effective hydrolysis (Kratky and Jirout, 2011). Another disadvantage is that mills can be damaged by stones and other hard materials, and equipment repairs can be very expensive.

Several researchers have investigated the effect of knife milling on biogas production. Menind and Novak (2010) found an approximately 10% higher gas yield was achieved after milling hay to 0.5 mm compared to 20–30 mm. Another study showed milling sisal fibres from 100 mm to 2 mm achieved an approximately 20 to 25% higher gas yield (Mshandete *et al.*, 2006). Reduction of particle size of wheat straw by knife mills from 12.5 to 1.6 mm requires 2.8–7.55 kWh/t¹ (Kratky and Jirout, 2011). To put this into context, the parasitic electrical demand of a continuously stirred tank reactor (CSTR) digesting slurries is around 10 kWh/t¹ (Murphy and McCarthy, 2005), and is much higher for other substrates. More research is required to say whether or not the electricity input for milling is justified by the electricity saved by improved mixing. Knife and hammer mills are generally used for dry biomass with a moisture content of up to 15% (Kratky and Jirout, 2011; Taherzadeh and Karimi, 2008). Hammer mills are relatively cheap and easy to operate, but have a slightly higher energy input in comparison to knife mills (Kratky and Jirout, 2011).

Thermal pre-treatment

During thermal pre-treatment, also called liquid hot-water (LHW) pre-treatment, the substrate is heated up under pressure to a maximum of 220°C, held for a specific time, cooled down and used in biogas plants. Substrates with low water content need additional water before thermal treatment. The presence of heat and water causes swelling of biomass by disrupting the hydrogen bonds that hold together crystalline cellulose and the structural complexes. Hemicellulose is also broken down during LHW, which aids swelling (Garrote *et al.*, 1999).

One example of thermal pre-treatment technology at large scale is so-called TDH (thermal hydrolysis, from the German ‘Thermo-Druck-Hydrolyse’). First, the substrate in the reactor is put under pressure of 20–30 bar. Using a heat exchanger, input material is heated to 140–180°C while the hydrolysed substrate is cooled down. Oil is heated using the exhaust gas stream and heats the substrate to hydrolysis temperature of 170–220°C. The



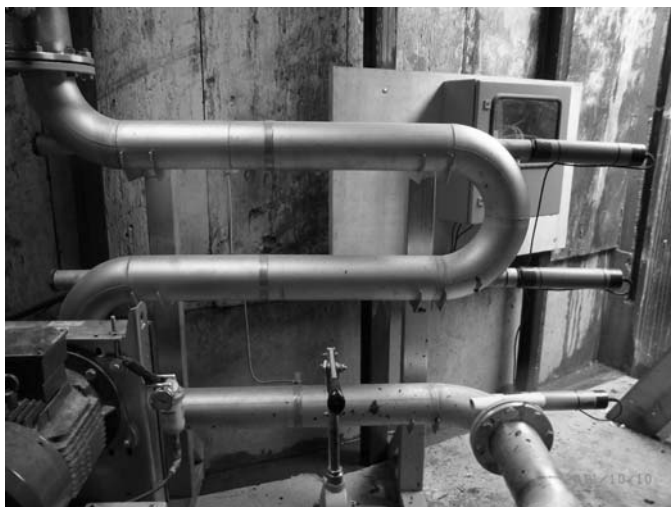
4.2 Large-scale TDH unit (source: R. Scheuchel GmbH, Ortenburg, Germany).

retention time is 20 minutes. The hydrolysed substrate is cooled down to almost process temperature using the heat exchanger. Finally, the pressure is released (Dinglreiter, 2007). Figure 4.2 shows such a unit.

Various studies have shown that thermal pre-treatment increases biogas yield only up to a certain temperature, and gas production decreases below this temperature. DiStefano and Ambulkar (2006) note the maximum temperature as 175°C for sewage sludge. Using TDH to pre-treat crops, the maximum temperature is 220°C (Dinglreiter, 2007). Thermal pre-treatment of brewers' spent grains shows a lower gas yield with pre-treatment above 160°C as compared with untreated substrate (Bochmann *et al.*, 2010). The maximum temperature depends on the composition of the substrate and also on the retention time of pre-treatment.

Ultrasonic treatment

Ultrasonic treatment is less suitable as a pre-treatment technology than for post-treatment of the liquid effluent from anaerobic digesters. The frequency of ultrasound is over 20 kHz; using these frequencies causes cavities or liquid-free bubbles to form and then implode, producing shockwaves in a process called cavitation. These forces cause the disruption of microbial cell walls in the liquid. In general, this technology is used for the treatment of sewage sludge from wastewater treatment plants, but the effect on biogas production from this ultrasonicated substrate is very low. Ultrasonic treatment only disintegrates microbiological biomass and not the input material (Onyeché *et al.*, 2002).



4.3 Electrokinetic disintegration unit (source: ATRES, Munich, Germany).

Electrokinetic disintegration

Electric fields are used for a variety of processes in modern biotechnology. Electrokinetic disintegration is mainly used for sewage sludge treatment. The main inhibiting factor for good anaerobic digestion of sewage sludge is the presence of flocs and aggregates, which are formed by negatively charged molecules on microbial extracellular polymeric substances forming ionic bonds with cations (Tyagi and Lo, 2011; Higgins and Novak, 1997). The application of an electrical field to sewage sludge disrupts these ionic bonds and thus breaks apart the flocs (Tyagi and Lo, 2011). It is also likely electric fields disrupt microbial cells by changing the charge of the cell membranes. It is not clear what effect, if any, this treatment has on lignocellulosic material. Some German companies produce electrokinetic disintegration devices in which the sludge is fed through a section of pipe with an electrode inside applying a voltage of typically around 30 kV (range 10–100 kV) (Hugo Vogelsang Maschinenbau GmbH, 2011; Süd chemie AG, 2011). Figure 4.3 shows such a unit. An increased biogas yield from sewage sludge of around 20% has been claimed (Süd chemie AG, 2011). It has also been claimed that the device can increase biogas production from agricultural residues (Hugo Vogelsang Maschinenbau GmbH, 2011), but a study by the Bavarian State Research Center for Agriculture, LfL, showed no significant increase in biogas production from agricultural residues (Lehner *et al.*, 2009). Like ultrasonication, electrokinetic disintegration may be better suited to post-treatment of the liquid effluent from anaerobic digesters or pre-treatment of substrates similar to sewage sludge.

4.3.2 Chemical pre-treatment

Chemical pre-treatment has been investigated using a range of different chemicals, mainly acids and bases of different strengths under different conditions. The use of temperature and chemicals together (thermochemical pre-treatment) is described in a later section.

Alkali treatment

As mentioned previously in this chapter, lignocellulosic materials are resistant to hydrolysis due to their structure and composition. Alkali pre-treatment removes the acetate groups from hemicellulose, which makes the hemicelluloses more accessible to hydrolytic enzymes. This enhances digestability. Alkali addition also causes swelling of lignocelluloses, although this is a secondary effect (Kong *et al.*, 1992). Lignin is also partly solubilised by alkali pre-treatment, and this allows more access to cellulose and hemicellulose. Alkali treatment can be carried out with different concentrations of lime, sodium hydroxide (NaOH) and potassium hydroxide (KOH).

There have been several reports of alkali treatment being effective for solid-state anaerobic digestion. He *et al.* (2008) showed an increase in biogas yield from rice straw of 27.3–64.5% using 6% NaOH for 3 weeks at ambient temperature. Liew *et al.* (2011) carried out simultaneous pre-treatment and methanisation using 3.5% NaOH on fallen leaves and showed that with an optimised substrate to inoculum ratio, the methane yield increased by 21.5%. Interestingly, when a sub-optimal substrate to inoculum ratio with too much substrate was used, the control tests produced extremely low levels of biogas, but the alkaline pre-treated tests increased methane yields 22-fold. These studies demonstrated that alkali pre-treatment can increase gas yield from hemicellulose-rich substrates and dissolve lignin complexes. However, it is important to note that alkali pre-treated substrates have high pH values. The above-mentioned experiments were carried out using small-scale batch tests but, during continuous fermentation, alkali pre-treatment leads to increased pH and salt build-up. The pH increase affects the ammonium–ammonia balance and inhibits methanisation, and high concentrations of cations like Ca^{2+} , K^{+} or Na^{+} lead to an inhibition of anaerobic digestion due to osmotic pressure (Chen *et al.*, 2008). However, the pH increase may be beneficial for substrates with low pH or high lipid content (e.g. as demonstrated by Beccari *et al.* (2001) with olive oil mill effluent and $\text{Ca}(\text{OH})_2$). This pre-treatment technology was deemed economically unattractive due to the high costs of bases (Chang *et al.*, 1997).

4.3.3 Biological pre-treatment

Microbiological pre-treatment

Microbial pre-treatment, also known as pre-acidification or multi-stage fermentation, is a simple kind of pre-treatment technology in which the first steps of anaerobic digestion (hydrolysis and acidogenesis) are separated from acetogenesis and methanogenesis. A two-stage digestion system is common for carrying out this kind of pre-treatment. The concept of carrying out digestion in separate vessels is similar to the multiple chambers of ruminant digestive systems. The pH value of the first digester (the pre-acidification step) should lie between 4 and 6, thereby inhibiting methane production (Deublein and Steinhauser, 2008; Thauer, 1998). This inhibition causes volatile fatty acids (VFAs) to accumulate. The gas produced during this pre-acidification step has high concentrations of carbon dioxide and hydrogen. The production of H_2 goes hand in hand with the production of fatty acids and is an important indicator to evaluate the pre-acidification step. The extent of H_2 production is most strongly influenced by pH: H_2 production at pH 6 is initially high and then stops and at pH 4 is lower but prolonged and greater overall (Liu *et al.*, 2006). Antonopoulou *et al.* (2008) demonstrated in continuous fermentation tests that H_2 concentration was 35–40% v/v of the total gas amount of the pre-acidification step.

Microbiological pre-treatment has a very positive effect on the degradation rate of substrates in anaerobic digestion. In general, cellulose, hemicellulose and starch-degrading enzymes work best between pH 4 and 6 at temperatures from 30 to 50°C, so this pre-acidification step increases the degradation rate by creating an optimal environment for hydrolytic enzymes, particularly for carbohydrate degradation. Liu *et al.* (2006) achieved an additional biogas yield of 21% at a hydraulic retention time of approximately 30 days. This was caused by higher degradation through increased hydrolytic enzyme activity.

Another positive effect of this pre-treatment method is on the methane concentration in the biogas. In addition to H_2 and VFA production, CO_2 is formed during the pre-acidification step. CO_2 can be present in three forms: at higher pH values in the form of the carbonate ion CO_3^{2-} ; at neutral pH as HCO_3^- ; and in acidic environments as CO_2 . Due to the low pH, most of the carbonate is in the form of CO_2 , which is volatile and is released into the hydrolysis gas produced from the pre-acidification step. This means that for the methanogenesis step, a higher CH_4 concentration is present in the gas phase. Nizami *et al.* (2012) produced a biogas with 71% methane content in a two-phase system digesting grass silage. The same grass silage produced a biogas with 52% methane content in a wet single-stage system.

In large-scale biogas plants, pre-acidification systems are offered by

several plant constructors, varying from continuous to batch pre-acidification systems. Continuous pre-acidification is offered, for example, by the companies AAT and Enbasys from Austria. Substrates are fed continuously in a two-reactor CSTR system. The daily removal of material to feed the second reactor is balanced by a feed of fresh material to the first reactor. Plug-flow reactors are also in use. This technology guarantees the treatment of the requested retention time, which is not given in the CSTR system. Batch pre-acidification digesters are completely emptied after a retention time of a few days and refilled with new substrates.

Enzyme addition

The purpose of enzyme addition is to break down polymers in the substrate, particularly lignocelluloses. A cocktail of enzymes is typically used, and may include cellulases, xylanases, pectinases and amylases. Enzymes can be applied in three different ways: by direct addition to the vessel of a single-stage anaerobic digestion; by addition to the hydrolysis and acidification vessel (first stage) of a two-stage system (see the previous section on microbiological pre-treatment); or by addition to a dedicated enzymatic pre-treatment vessel. The addition of enzymes to anaerobic digestion has been analysed in different studies. Romano *et al.* (2009) analysed the effect of enzyme addition on anaerobic digestion of a type of pasture grass, wheat grass. The enzyme addition showed a positive impact on solubilisation of the substrate. In this study, no additional gas yield was measured, but a slightly faster degradation rate was found in a single-stage system. In a different study, an additional gas yield was achieved using two-stage digestion of brewers' spent grains with enzyme addition in the acidification stage (Bochmann *et al.*, 2007). Higher VFA production was also achieved through enzyme addition. Ellenrieder *et al.* (2010) analysed the addition of single enzymes like cellulose, amylase or pectinase to maize and grass silage, but no additional benefit on gas yield was determined.

4.3.4 Combined processes

Steam explosion

The principle of steam explosion is related to thermal pre-treatment. The substrate is heated in a closed system to a temperature of 160 to 220°C, causing a rise in pressure. After a process specific retention time (between 5 and 60 minutes), pressure is released abruptly. This sudden drop in pressure causes intracellular water to evaporate. Cell walls are disrupted, causing substrates to lose their structure. Due to the long retention time and high temperatures, the Maillard reaction occurs and Maillard products are

Table 4.1 Biogas yield of steam-exploded substrates compared with untreated substrates

	Biogas yield (m ³ CH ₄ /t fresh matter)			
	Slaughterhouse residues	Maize silage	Straw	Reeds
Before treatment	450	200	280	210
After treatment	500	250	400	350

Source: Coramexport (2011).

formed. These products can inhibit anaerobic digestion. Many studies in the field of ethanol production have shown high furfural and hydroxymethylfurfural (HMF) production as a result of long retention times and high temperature. Benjamin *et al.* (1984) and Bochmann *et al.* (2011) demonstrated that these products have a negative impact on anaerobic digestion. Another negative aspect is that the recovery of heat from this pre-treatment is impossible. However, using steam explosion allows substrates such as hay or straw to be used for biogas production. Bauer *et al.* (2009) analysed steam explosion tests of straw and showed calculations of ethanol and biogas potentials. Table 4.1 shows gas yields with and without steam explosion.

Extrusion

Extrusion is a process adapted from other industries such as metal and plastic processing industries. In these industries, material is fed into an extruder and conveyed by screw along a tube, where it is exposed to high pressure, temperature and shear forces. The material is subsequently pushed out of a hole of specific shape to form the final product, which could be a pipe or a sheet. Biogas substrates in extruders are subjected to the same forces, causing tough fibres to break and the plant cells to lyse. In addition, as the substrate leaves the extruder, the sudden drop in pressure causes evaporation of intracellular water, as in steam explosion.

Extrusion tests for biogas substrates typically use twin-screw extruders where the screws rotate counter wise. Extruders are available at ratings from 11 kW to a 55 kW; substrate output is in the range 0.9 to 4.0 t/hour respectively. Depending on the consistency required at the end, the substrate can be placed under a pressure of up to 300 bar at temperatures from 60 to 300°C. For biomass with a total solid content of 30 to 35%, the temperature should not exceed 100°C due to water evaporation and substrate drying.

Extrusion increases the specific surface area of biomass, which allows easier access by hydrolytic enzymes to the chemical bonds. The increasing availability of the biomass results in faster methane production. This facilitates higher organic loading rates in the reactors.

Many biomethane potential (BMP) tests (see Chapter 3) have been carried out with extruded biomass, and additional methane production was found for most of the treated substrates. Hjorth *et al.* (2011) analysed the effect of the extrusion process on anaerobic degradation of straw, unsiled grass, the solid fraction of manure from a screw press, the solid fraction of manure after flocculation and deep litter from cattle. After 28 days of BMP tests, the extruded straw showed up to 70% more methane production than the untreated straw and after 90 days of BMP tests, the methane yield of extruded straw was 11% higher than that of the untreated. This shows that biogas production from straw was faster when extrusion was used to pre-treat it, but the data had a very high standard deviation so the additional benefit may be smaller than presented. For the extrusion process, approximately 10–15 kW per tonne of substrate is needed; this is a similar value to the parasitic electrical demand of a CSTR digesting slurry (Murphy and McCarthy, 2005).

A major problem with extrusion pre-treatment technology is the screws, which have to be changed after a few months due to abrasion. As with other mechanical pre-treatment technologies, stones or metallic materials in the substrates severely reduce the lifetime of the screws. This has a negative impact on the economics of the extrusion process.

Thermo-chemical pre-treatment

During thermo-chemical pre-treatment, the effects of thermal and chemical influence are combined. Different kinds of bases and acids can be used, but ammonia (e.g. the AFEX process) or different kinds of solvents (e.g. the organosolv process) are also used. Temperatures from 60 to 220°C have been studied. Pre-treatment temperatures of more than 160–200°C showed a drop in methane production, depending on the input material (DiStefano and Ambulkar, 2006; Delg enes *et al.*, 2000; Penaud *et al.*, 1999).

The thermal influence during alkali pre-treatment of waste activated sludge leads to a higher chemical oxygen demand (COD) solubilisation (100%) and a higher gas yield (20%) when compared with alkali pre-treatment (Kim *et al.*, 2003). Inhibition effects of alkali addition are similar to alkali pre-treatment without thermal influence.

Zhang *et al.* (2011) analysed the thermal pre-treatment of cassava with acid addition. Sulphuric acid was used in concentrations of 1.32–4.68% (w/w) and the temperature was 150–170°C. The reaction time was 10–36 minutes. A 57% higher gas yield was found for pre-treated cassava compared with untreated. The pre-treatment parameters that obtained the maximum gas yield were 160°C, 3% H₂SO₄ and 20 minutes retention time (Zhang *et al.*, 2011).

The influence of thermal, chemical and thermo-chemical pre-treatment on

dewatered pig manure was analysed by Rafique *et al.* (2010). High concentrations of lime (5%) showed maximum enhancement of gas yield at 70°C. An increase of 78% biogas and 60% methane was observed.

4.4 Conclusion and future trends

A wide range of technologies are available for the pre-treatment of biogas substrates, based on a variety of principles. When substrate composition and pre-treatment technology are appropriately matched, the bioavailability of the substrate increases. This can lead to an improved performance of biogas reactors in terms of gas yield and degradation rate during anaerobic digestion. The energy balance and costs must be considered. The energy demand of pre-treatment depends on the technology used. In most cases, pre-treatment methods with a low energy demand give smaller benefits to the rate of degradation and corresponding biogas yield as compared with pre-treatments with high energy input, but this is not always the case. Higher gas yields result from the degradation of lignocellulose complexes and increase in availability of recalcitrant substances. Many pre-treatment technologies do not increase the biogas yield, but increase the degradation rate. The energy demand of pre-treatment technology is important for a number of reasons, including sustainability criteria as required by the EU Renewable Energy Directive. A negative energy balance can also lead to an uneconomical process. As high investment costs are needed in many cases, a corresponding significant increase in gas yield is necessary to make the process financially feasible.

Many principles of pre-treatment technology were and are developed for other purposes, such as ethanol production from lignocellulosic feedstocks. The influence of pre-treatment technologies on anaerobic digestion has been investigated in recent years and there is still a huge demand for optimisation of these technologies for the biogas industry. Ongoing research is especially important to bring some technologies to a financially feasible level. The investment costs for pre-treatment of recalcitrant substrates are high at the moment due to high expenditure in process engineering. However, if these costs are decreased to an affordable level, new substrates will be made available for biogas production. In closing, it should be mentioned that pre-treating all substrates with one technology is not realistic and pre-treatment may not be financially viable or improve the energy balance for substrates with high degradation rates.

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Fundamental science and engineering of the anaerobic digestion process for biogas production

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Abstract: The aim of this chapter is to explain, in a simplified manner, the complex microbiological process of anaerobic digestion and detail the relationship between feedstock, anaerobic digester and methane production. The chapter first reviews basic microbiology and explores the interplay between the different groups of bacteria, the conditions under which they prosper and potential sources of inhibition. Then, the chapter deals with engineering aspects – categorisation of feedstocks, methane production per unit of feedstock, reactor configurations, mass and energy balance of digestion systems, up-scaling laboratory systems to commercial reality and modelling. In the analysis, an emphasis is placed on high solid content feedstocks. Two different feedstocks are highlighted – the organic fraction of municipal solid waste and grass silage.

Key words: anaerobic bacteria, methanogens, methane, digester configuration.

5.1 Introduction

5.1.1 Bacterial process and biogas

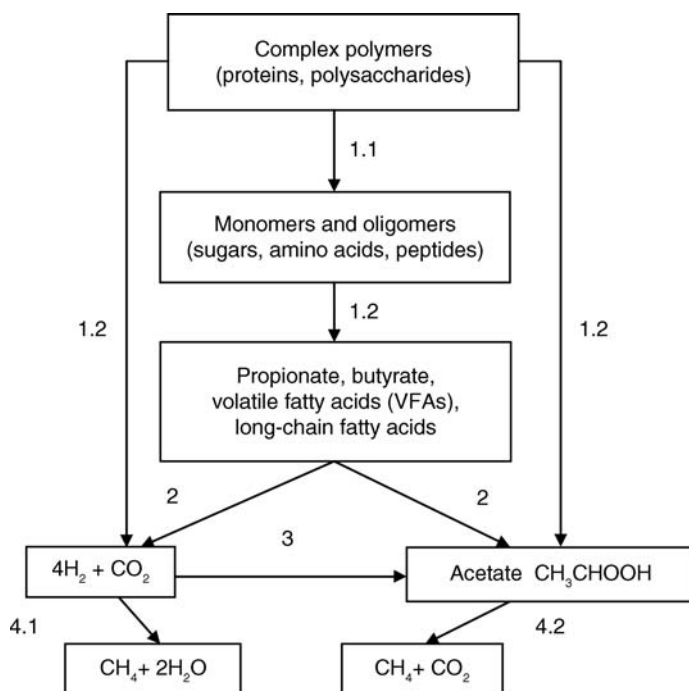
Anaerobic processes are quite complex microbial processes that take place in the absence of oxygen. Bacteria are mainly involved in the process but higher trophic groups such as protoza and anaerobic fungi may be involved. The microbial population contains many diverse genera (types) of obligate anaerobic bacteria (strictly anaerobic) and facultative anaerobic bacteria (i.e. with the ability to function as aerobes in the presence of oxygen).

The process brings about the conversion of organic raw materials to biogas. This biogas is dominated by methane (50–70%) and carbon dioxide (30–50%). Considering methane has a higher heating value (HHV) of ca. 37.8 MJ/m_n^3 and carbon dioxide has no energy associated with it (as it is the product of complete combustion), biogas has an energy content of between 19 and 26 MJ/m_n^3 . Hydrogen sulphide is also present in the biogas; the proportion depends on the characteristics of the feedstock. Typically, biogas from animal slurry has a higher content of H_2S than biogas from crops. The bulk of the energy content of the material undergoing biodegradation is conserved in the methane content, and only a minor fraction is made available for bacterial growth and reproduction.

5.1.2 History

The first documented account of an anaerobic reactor was in France in 1891. The Mouras Automatic Scavenger was an airtight chamber in which organic material was liquefied. In 1895 in Exeter, England, an engineer by the name of Cameron invented the septic tank. It was utilised for the preliminary treatment of municipal wastewater downstream of the coarse and fine screens. The methane gas produced was used to heat and light the wastewater treatment plant.

The septic tank evolved firstly to the Travis tank (1904) and then to the Imhoff tank (1905). The Imhoff tank was utilised as a primary sedimentation step in wastewater treatment plants, with sludge storage within the tank. This sludge was stored for months in the chamber where it was biodegraded by anaerobic bacteria. After storage, it was inoffensive and easy to dispose of. In 1927, Ruhrverband installed the first sludge heating apparatus in a separate digestion tank. In the 1930s, a detailed description of anaerobic digestion was published in the USA (Buswell and Hatfield, 1936). Much of the commercial applications of anaerobic digestion in the latter half of the 20th century were applied to either high-strength wastewaters (brewery and creamery wastewater with high organic loading rates) as a precursor to aerobic treatment or to sewage sludge and agricultural slurries. Anaerobic digestion is now viewed as a mature technology for the treatment of wastewater, for the treatment of slurries and sludges, for digestion of the organic fraction of municipal solid waste (OFMSW) and, more recently, for renewable energy production through digestion of crops (Murphy *et al.*, 2011).

**1 Acidogenic bacteria**

1.1 Hydrolytic bacteria

1.2 Fermentative bacteria

2 Acetogenic bacteria**3 Homoacetogenic bacteria****4 Methanogenic bacteria**

4.1 Hydrogenotrophic methanogenic bacteria

4.2 Aceticlastic methanogenic bacteria

5.1 Four trophic groups involved in anaerobic processes (adapted from Colleran, 1991a).

5.2 Microbiology

Four different trophic groups are currently recognised in anaerobic processes (see Fig. 5.1). The coordinated activity of these trophic groups as a whole ensures stability.

5.2.1 Acidogenic bacteria

Known as anaerobic acidogenic bacteria, this group consists of fermentative and hydrolytic bacteria. The hydrolytic bacteria hydrolyse (i.e. break down polymers to monomers; make soluble material of particulate material) and

the fermentative bacteria ferment the resultant monomers to a wide range of fermentation end products. End products of the acidogenic stage include acetic acid, hydrogen and carbon dioxide. However, the majority of the products are higher carbon number volatile fatty acids (VFAs) such as propionate, butyrate and alcohols.

5.2.2 Acetogenic bacteria

The obligate proton-reducing (OPR) acetogenic bacteria are unique as they are obligate syntrophs (i.e. they must act together with bacteria in a different trophic group to digest a substrate). They cannot be cultivated in a pure culture; their existence was not discovered until 1967, by Bryant and co-workers (McCarty, 1981). Their energy is derived from substrates if the hydrogen partial pressure is maintained at a very low level. Hydrogen is a product of their own metabolism and is toxic to them. These acetogenic bacteria require the syntrophic action of a H_2 -utilising species. The role of the OPR acetogenic bacteria is crucial to the overall anaerobic process as they convert the fermentative intermediates (VFAs) to methanogenic substrates, H_2 , CO_2 , acetic acids and unicarbon compounds.

5.2.3 Methanogenic bacteria

This group consists of hydrogenotrophic methanogenic bacteria and aceticlastic methanogenic bacteria. The hydrogenotrophic bacteria utilise the H_2 which the OPR acetogens produce. H_2 uptake by the methanogens is very efficient, having an affinity of parts per million, which ensures very low hydrogen partial pressure. The relationship between OPR acetogens and hydrogenotrophic methanogenic bacteria is an excellent example of syntrophic mutualism: bacteria in different trophic groups converting propionate, butyrate and long-chain fatty acids to methane and water.

Species of only two genera *Methanosarcina* and *Methanothrix* can produce methane from acetic acid and be termed aceticlastic. Approximately 70% of methane produced comes from acetate and aceticlastic methanogens. It is usual in the literature to read that methanogens have slow doubling times (reproduction rates), but this is not entirely true: hydrogenotrophic methanogens are very efficient and have relatively fast doubling times (Pfeffer, 1979). Aceticlastic methanogens are, however, relatively inefficient in acetate uptake and as a result have slow doubling times.

5.2.4 Homoacetogenic bacteria

Hydrogen-consuming acetogens appear to be outcompeted by methanogens for hydrogen. The net result, however, is the maintenance of low hydrogen partial pressures and increased significance of acetate as an immediate methane precursor (Zeikus, 1979).

5.2.5 Stoichiometry of acetogenic bacteria

In 1967, Bryant and co-workers showed that the *M. Omelianski* culture contained two bacterial species (McCarty, 1981). One converted ethanol ($\text{CH}_3\text{CH}_2\text{OH}$) to acetate (CH_3COOH) and hydrogen (H_2); the other converted carbon dioxide (CO_2) and hydrogen to methane (CH_4). So, for the complete oxidation of a simple compound such as ethanol to CO_2 and CH_4 contributions from three separate species would be required, as follows.

			ΔG (kJ/reaction)
Species 2	$\text{CH}_3\text{CH}_2\text{OH} + \text{H}_2\text{O} = \text{CH}_3\text{COO}^- + \text{H}^+ + 2\text{H}_2$		+5.95
Species 4.1	$2\text{H}_2 + 0.5\text{CO}_2 = 0.5\text{CH}_4 + \text{H}_2\text{O}$		-65.45
Species 4.2	$\text{CH}_3\text{COO}^- + \text{H}^+ = \text{CH}_4 + \text{CO}_2$		-28.35
Net	$\text{CH}_3\text{CH}_2\text{OH} = 1.5\text{CH}_4 + 0.5\text{CO}_2$		-87.85

- Species 2: OPR acetogenic bacteria. The standard free energy of the reaction (ΔG) is positive. Thus, for this reaction to occur, the hydrogen partial pressure has to be lowered. This is explained by Le Chatelier's principle, which states that if some stress (in this case a reduction in the concentration of the products) is brought to bear on a system in equilibrium a reaction occurs which displaces the equilibrium in the direction which tends to undo the effect (towards the product).
- Species 4.1: Hydrogenotrophic methanogenic bacteria form a syntrophic association with the acetogenic bacteria. The standard free energy of the reaction is relatively high in the negative direction, indicating the affinity of the methanogen to hydrogen.
- Species 4.2: Aceticlastic methanogenic bacteria. The standard free energy of the reaction is less negative than for its hydrogenotrophic relation, indicating the lower affinity of methanogens for acetate.

In the theoretical degradation of ethanol two thirds of the methane comes from acetate and one third comes from hydrogen.

5.2.6 Sulphate-reducing bacteria

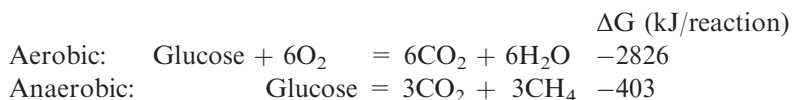
Sulphate-reducing bacteria (SRB) can utilise multicarbon compounds and methanogenic substrates: carbon dioxide, hydrogen and acetate. With high additions of sulphate, the SRB metabolise unicarbon compounds and hydrogen, more effectively to the detriment of the methanogens. Due to the syntrophic nature of anaerobic processes, this affects all trophic groups (Zeikus, 1979).

5.3 Microbial environment

5.3.1 Reducing effects

By its very definition, anaerobic digestion takes place in the absence of molecular oxygen and the environment changes from an oxidising state to a reducing one. This may be explained in chemical terms by noting that alternate electron acceptors must be found to replace molecular oxygen. Usually, carbon atoms associated with organic compounds will become electron acceptors and will be reduced while other organic compounds will be oxidised to carbon dioxide and volatile acids. The end product of this reaction still contains large amounts of energy (potential to accept electrons) in the form of methane.

For the bacterial cell to yield enough energy for cell growth and maintenance, a large quantity of substrate needs to be processed (Eckenfelder *et al.*, 1988). Thus, bacterial production is much less than would occur in aerobic conditions with oxygen as the electron acceptor (Colleran, 1991b). The sludge/bacteria produced from the aerobic conversion of glucose is 450 kg of dry microbial biomass per tonne of chemical oxygen demand (COD) converted. This may be compared with 45 kg of dry microbial biomass per tonne of COD converted in the anaerobic reaction (Colleran, 1991b) as follows:



For industrial wastewater treatment this offers significant advantage to anaerobic processes over aerobic processes. Dissolved oxygen as low as 0.1 mg/l can completely inhibit methanogenic growth (Casey, 1981). Not only oxygen but other highly oxidised materials, which are electron acceptors, may inhibit methanogenesis (Pfeffer, 1979). Nitrites, nitrates and sulphates are examples of such oxidised materials.

5.3.2 Volatile fatty acids and bicarbonates

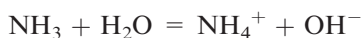
The acid base system that controls pH in anaerobiosis is the carbonate acid base system. If the total volatile acid of the system is low the bicarbonate alkalinity is a measure of the total alkalinity of the system. Should the volatile acid concentration increase, bicarbonate alkalinity will neutralise the acids.

Un-ionised volatile acids are toxic to methanogenesis if the pH is less than 6. Un-ionised aqueous ammonia is toxic to methane-forming microorganisms at pH levels greater than 8. Thus, high concentrations of volatile acids can be tolerated if sufficient buffering capacity exists to prevent the formation of free acids and a shift in pH (Noone, 1990).

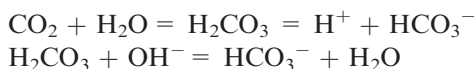
Most problems in anaerobic digestion can be attributed to an accumulation of acids and a fall in pH (Archer and Kirsop, 1990). The adverse effect of VFAs on methanogenic bacteria is particularly problematic as VFAs are intermediates of the process. The effect of a decrease in pH is described by Casey (1981) as follows. The growth of methanogens is inhibited below a pH of 6.6. However, the acidogenic bacteria continue to function until the pH drops to 4.5–5. The result is a rapid accumulation of VFAs. A useful indicator of impending process failure is the accumulation of acetate followed by propionate (Pfeffer, 1979). The following rules of thumb may be applied to the management of a carbonate acid base system (Water Pollution Control Federation (WPCF), 1987).

- Volatile acids/alkalinity > 0.3–0.4 indicates that the process is unstable and that corrective action is required.
- Volatile acids/alkalinity > 0.8 indicates that the process is failing due to pH depression and inhibition of methanogenesis.

Microorganisms may degrade proteins, and produce ammonia. Ammonia reacts with water to produce hydroxide ions in the following reaction.



Carbon dioxide, formed by anaerobiosis, partly escapes to gas phase, however it is relatively soluble in water. In solution it reacts with hydroxide ions in the system to form bicarbonate ions, HCO_3^- .



Thus, the higher the protein content of the substrate, the more alkaline radicals are available to form bicarbonate ions with aqueous CO_2 . At lower temperatures, according to Henry's law, more carbon dioxide goes into solution and more bicarbonate ions may be formed, leading to a higher buffering capacity. Thus, substrates that which are treated anaerobically at

mesophilic temperatures will have higher buffering capacities if hydroxide ions are available than if treated at thermophilic temperatures.

Ammonia nitrogen concentrations in the range of 1500–3000 mg/l at pH levels above 7.4 are said to be toxic, while levels above 3000 mg/l are supposed to be toxic at all pH levels (Van Velsen and Lettinga, 1979). It has been found, however, that anaerobic processes have operated efficiently with higher levels of ammonia nitrogen (Sugrue *et al.*, 1992; Van Velsen and Lettinga, 1979); this is a reflection of the ability of the methanogenic population to acclimatise to toxins. Nizami *et al.* (2011b) found ammonia nitrogen levels of 2400 mg/l in a wet digestion process treating grass silage. Marin-Perez *et al.* (2009) state that the inhibition level for grass digestion is 4700 mg N/l. A slaughterhouse waste digester in Austria (International Energy Agency (IEA), undated) found ammonia nitrogen levels varied between 4500 and 7500 mg/l depending on substrate composition. At higher ammonia levels, gas production decreased. Undissociated ammonia (NH_3) is believed to be the toxic form of ammonia nitrogen and its production is temperature dependent. At lower temperatures, less NH_3 is produced. The slaughterhouse waste digester in Austria maintained the temperature of the digester at or below 35°C to minimise production of NH_3 (IEA, undated).

5.3.3 Nutrients, trace elements and inhibition

An average microorganism cell contains nitrogen, phosphorous and sulphur in quantities of 12, 2 and 1% of dry bacteria biomass respectively. Anaerobic metabolism is such that their growth rate is approximately 10% of that of aerobes. Thus, for wastewater treatment, nitrogen (N) and phosphorous (P) are required in the ratio of 700:5:1 (biological oxygen demand:N:P) as compared with aerobic metabolism, which requires the ratio of 100:5:1 (Wheatley, 1990).

Sulphur, potassium, calcium, magnesium, chloride and sulphate ions are also required for proper digestion. Trace amounts of iron, copper, zinc, manganese, molybdenum and vanadium are also required for cell growth (WPCF, 1987). Sulphides, which are required by many methanogens as a sulphur source for growth, are inhibitory to methanogens in high concentrations (Zeikus, 1979).

Sulphur compounds tend to be particularly problematic as they cause precipitation of essential trace nutrients such as iron, nickel, copper and molybdenum, which are insoluble at low redox potentials. SRB have lower doubling times than methanogens and utilise similar substrates and hence divert some of the anaerobic process to H_2S production. H_2S interferes with intracellular microbial metabolism by binding with essential enzymes and co-enzymes (Wheatley, 1990).

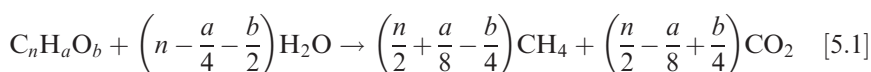
Heavy metal ions such as Cu^{++} and Zn^{++} , alkaline and earth alkaline

metal ions such as Na^+ , NH_4^+ , K^+ and Ca^+ are also found to be inhibitory. Heavy metal toxicity only seems to be concerned with free metal ions. The presence of H_2S in the biogas indicates a sufficient number of sulphur compounds to remove the toxic effect of heavy metals, especially Cu^{++} (Van Velsen and Lettinga, 1979). Chlorinated solvents, biocides, pesticides and antibiotics are also inhibitory to the anaerobic process. Only materials in solution can be toxic to biological life (Pfeffer, 1979).

The serial processes of an anaerobic system, whereby the substrate for one group may be the end product of another group, are theoretically much more vulnerable to toxicities than aerobic processes, which are dominated by parallel biochemical pathways (the initial substrate is available to all bacterial groups). Methanogens are the most sensitive to inhibiting agents but have a very forgiving nature (Vochten *et al.*, 1988). Toxicity is reversible in many cases and a significant acclimation potential is observed if sufficient time is allowed.

5.4 Gas production and feedstocks

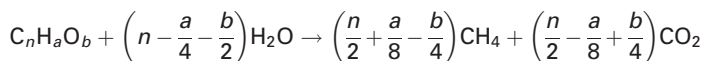
The main digestible components of solid waste are carbohydrates, proteins and fats. The carbon to nitrogen ratio to yield maximum methane production is 25:1 (Hobson, 1990). With knowledge of the chemical composition of a waste outlined in equation 5.1, the quantity of methane can be predicted from the stoichiometric formula (Buswell and Hatfield, 1936)



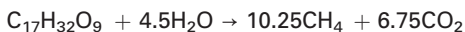
The following details an example based on the organic fraction of municipal solid waste (OFMSW). The methodology is described by Tchobanoglous *et al.* (1993). An ultimate analysis of the dry solids (DS) of OFMSW is outlined in Table 5.1 (48.3% C, 7.6% H_2 , 35.8% O_2 , 3.3% N_2). The remaining 5% of DS is inert (or ash). Knowledge of the atomic weights of the elements allows stoichiometric description of the DS of OFMSW as $\text{C}_{17}\text{H}_{32}\text{O}_9\text{N}$.

Table 5.1 Chemical composition of OFMSW

Component	Number of atoms per mole	Atomic weight	Weight contribution of each element	%
Nitrogen	2.36 (1)	14	33	3.3
Carbon	40.25 (17)	12	483	48.3
Hydrogen	76.00 (32)	1	76	7.6
Oxygen	22.38 (9)	16	358	35.8
Total			950	95

Box 5.1 Proportion of CH₄ and CO₂ based on equation 5.1

$$n = 17, a = 32, b = 9$$



$$380 \quad + 81 \quad \rightarrow 164 \quad + 297$$

$$461 \quad \rightarrow 461$$

$$285 \text{ kg VS} + 61 \text{ kg water} \rightarrow 123 \text{ kg CH}_4 + 223 \text{ kg CO}_2 \text{ [285 kg VS/t OFMSW]}$$

$$200 \text{ kg VDS}_{\text{dest}} + 43 \text{ kg water} \rightarrow 86 \text{ kg CH}_4 + 156 \text{ kg CO}_2 \text{ [70\% destruction]}$$

$$\text{Density of CH}_4 = 16/(22.412 \text{ m}_n^3/\text{kg}) = 0.714 \text{ kg/m}_n^3$$

$$\text{Density of CO}_2 = 44/(22.412 \text{ m}_n^3/\text{kg}) = 1.96 \text{ kg/m}_n^3$$

$$\text{Thus the proportion of gas by volume} \rightarrow 120 \text{ m}_n^3 \text{ CH}_4 + 80 \text{ m}_n^3 \text{ CO}_2 = 200 \text{ m}_n^3 \text{ biogas}$$

$$\text{Thus biogas contains approximately} \rightarrow 60\% \text{ CH}_4 + 40\% \text{ CO}_2 \text{ by volume}$$

$$\text{Methane production is } 421 \text{ l/kg VS added}$$

$$\text{Maximum production of methane (100\% destruction of VS) is } 601 \text{ l/kg VS added}$$

$$1 \text{ m}_n^3 \text{ CH}_4 \approx 37.78 \text{ MJ}; 1 \text{ m}_n^3 \text{ biogas @ } 60\% \text{ CH}_4 = 22.7 \text{ MJ/m}_n^3$$

For the purposes of this example, it is estimated that the moisture content of the OFMSW is 70%; 95% of the solids are volatile. Thus, one tonne of OFMSW corresponds to 300 kg DS and 285 kg volatile solids (VS). A well-designed digester aims at a minimum of 70% destruction of VS or 199.5 kg VS/t OFMSW. The number of molecules in a unit volume under standard conditions is the same for all gases. This volume is 22.412 m³/kg. Methane has an energy value of 37.78 MJ/m³. Box 5.1 shows a calculation of the proportion of CH₄ and CO₂ based on equation 5.1. The biogas has 60% CH₄ and has an energy value of 22.7 MJ/m³. A total of 200 m³ of biogas is produced, which is equivalent to 4.5 GJ/t OFMSW. The maximum production of methane is calculated as 600 l/kg VS added. In this case, with 70% destruction of volatiles, the methane production equates to 421 l/kg VS added.

In Box 5.2 the energy value of the feedstock is obtained using the modified Dulong formula (equation 5.2) (Tchobanoglous *et al.*, 1993). This would suggest 406 l CH₄ is produced per kilogramme VS added (good agreement with a slight discrepancy with the value obtained in Box 5.1).

Box 5.3 presents a relationship between VS and COD. In a two-stage process where hydrolysis is separated from methanogenesis, each kilogramme of VS produces between 1.57 and 1.60 kg COD and each

Box 5.2 Biogas production based on volatile solids (VS) destruction

$$\text{Energy value (kJ/kg)} = 337C + 1419(H - 1419\frac{O}{8}) + 93S + 23.26N \quad [5.2]$$

where C , H , O and N are the proportions of dry solids which are carbon, hydrogen, oxygen, sulphur and nitrogen respectively. C is 48.3% of dry solids and is thus 50.84% of volatile solids ($48.3/0.95$); similarly H is 8% of VS, O is 37.7% of VS and N is 3.47% of VS.

$$\text{Energy value of 1 kg VS} = 337(50.84) + 1419[8 - (37.7/8)] + 23.26(3.47)$$

$$\text{Energy value} = 17133 + 4665 + 80.7 = 21878 \text{ kJ/kg VS} = 21.9 \text{ MJ/kg VS}$$

300 kg DS/t OFMSW; 285 kg VS/t OFMSW; 200 kg VS destroyed/t OFMSW (70% destruction)

$$4.38 \text{ GJ converted/t OFMSW} = 116 \text{ m}_n^3 \text{CH}_4/\text{t OFMSW} \text{ or } 116 \text{ m}_n^3 \text{CH}_4/285 \text{ kg VS} = 406 \text{ l CH}_4/\text{kg VS}$$

Box 5.3 Relationship between VS and COD in a two-stage process

1 kg of COD generates 350 l CH₄ (Nizami *et al.*, 2009; Sperling and Chernicharo, 2004)

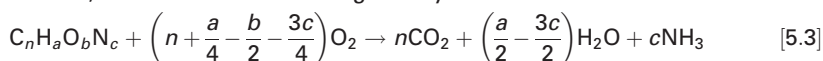
Thus 1 kg COD generates 13.22 MJ

$$1 \text{ kg VS} = 20.74 \text{ MJ}$$

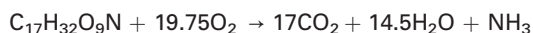
Thus 1.57 kg COD may be generated from 1 kg VS.

The basis for the COD test is that nearly all organic compounds can be fully oxidised to carbon dioxide with a strong oxidising agent under acidic conditions (Nizami *et al.*, 2009).

The amount of oxygen required to oxidise an organic compound to carbon dioxide, ammonia and water is given by



$$n = 17, a = 32, b = 9, c = 1$$



$$394 + 632 \rightarrow 748 + 261 + 17$$

$$1026 \rightarrow 1026$$

$$394 \text{ kg VS: } 632 \text{ kg O}_2$$

$$1.6 \text{ kg O}_2 \text{ to oxidise 1 kg VS}$$

kilogramme of COD generates 350 l CH₄. Thus, in a two-stage system, the maximum production of methane is of the order of 560 l CH₄/kg VS. The values for methane production per kilogramme of VS for OFMSW may be compared with documented values for crop digestion (Table 5.2).

Gases dissolve at different rates (see Table 5.3). Carbon dioxide is much more soluble than methane. At lower temperatures, more CO₂ goes into solution, causing a higher percentage of CH₄ in the gas. This temperature

Table 5.2 Methane yields for selected crops

Crop	Yield(l) CH ₄ /kg VS
Maize (whole crop)	205–450
Wheat (grain)	384–426
Grass	298–467
Clover	300–350
Oilseed rape	240–340
Potatoes	276–400
Fodder beet	420–500

Source: Murphy *et al.* (2011)**Table 5.3** Solubility of some relevant gases in water (millilitres of gas reduced to 0° C and 760 mm Hg per litre of water when the partial pressure is 760 mm Hg)

	Temperature (°C)			
	0	10	20	30
CH ₄	55.6	41.8	33.1	27.6
N ₂	23	18.5	15.5	13.6
O ₂	49.3	38.4	33.4	26.7
CO ₂	1710	1190	878	665

solubility difference between methane and carbon dioxide is utilised in gas upgrading.

Anaerobic digestion usually takes place within three temperature ranges

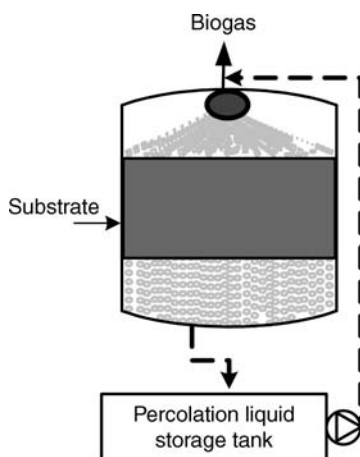
- thermophilic, 55–60°C
- mesophilic, 35–40°C
- psychrophilic, <20°C

In the mesophilic range, gas production decreases at 43°C and inhibition sets in. Similar occurrences take place at 63°C in the thermophilic range (Pfeffer, 1979). It is recommended (WPCF, 1987) that fluctuations of 1°C or greater do not occur in digesters as this has an unsettling effect on the microbial community.

5.5 Reactor configuration

5.5.1 Types of reactors

The optimal reactor design and configuration is a function of the feedstock characteristics. The feedstock must be assessed for characteristics, including DS content, volatility of solids, biodegradability, density, functional specific gravity (potential to float) and particle size. Reactors may be dry or wet, batch or continuous, one-step or multi-step and one-phase or multi-phase

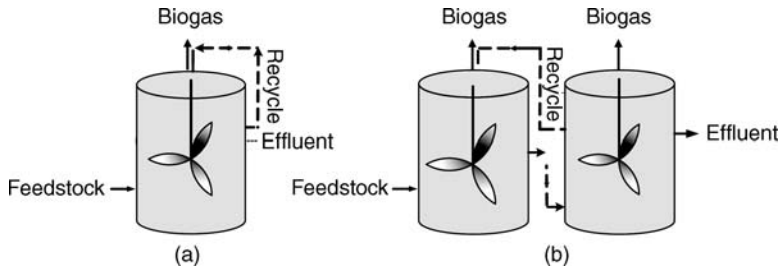


5.2 One-stage dry batch digester with sprinkling of liquor in a closed loop (adapted from Nizami and Murphy, 2010).

(Nizami and Murphy, 2010). Reactors may be operated under mesophilic or thermophilic temperature conditions.

5.5.2 Dry batch reactors

Reactors may take the form of a simple batch process (Fig. 5.2); this is commonly used for feedstocks with solids content of 30–40% (Hobson, 1990). The feedstock is fed to the digester, and gas production initiates, increases, peaks, decreases and then ceases. At this stage the batch is opened and approximately half of the feedstock is removed. The remainder is left as inoculum for the next batch (Nizami and Murphy, 2010). The effective retention time is therefore of the order of 50% greater than the period between feeding frequency. Typically, liquor drained from the digester is showered on the feedstock and fed in a closed loop, repeatedly showering the process. The advantage of the batch digester is its simplicity. The parasitic energy demand is low. The solids content is high so a relatively small amount of thermal energy input is required. The processing required is also low, leading to a low electrical parasitic demand. The benefit of the system is exemplified when treating waste such as OFMSW. Contaminants are not of issue for the system; if, for example, a piece of metal is in the feedstock this will not encroach on any moving part. The system typically employs existing agricultural or construction equipment to insert and remove the feedstock. Vertical garage door systems are often employed in these systems. The main disadvantage of the system is that it may not maximise the methane production per unit of feedstock. For commercial developments, numerous batches are employed that are fed sequentially to



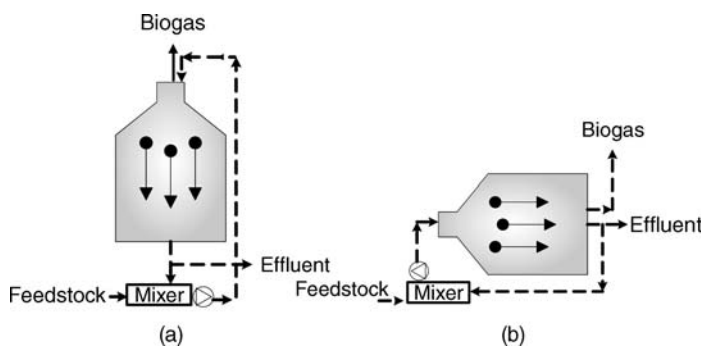
5.3 (a) One-step and (b) two-step continuous digestion with recirculation of liquid digestate (adapted from Nizami and Murphy, 2010).

achieve a relatively homogenous production of gas (Nizami and Murphy, 2010).

5.5.3 Continuously stirred tank reactors

Commonly known as CSTRs, engineers have more experience with this type than any other reactor. The reactor is a continuous wet process, treating feedstock with between 2 and 12% DS. There are numerous such facilities throughout the world treating sewage sludge, agricultural slurries and crops. The mixing systems are a crucial design element of this process. Various systems are employed, for example, in recycling biogas – paddle stirrers that rotate vertically in a circular motion about a horizontal axis, paddles that rotate horizontally about a vertical axis and inclined paddle stirrers. Typically, the hydraulic retention time (HRT) is the same as the solid retention time (SRT). Due to the slow growth rate of aceticlastic methanogenic bacteria and the syntrophic nature of all trophic levels of bacteria in the anaerobic process, failure would occur if the retention time were lower than the doubling time of these bacteria, due to washout. Organic loading rates tend to be in the range 1–4 kg VS/m³ reactor/day (Murphy *et al.*, 2011).

The system may be operated as a single-step system but more often a two-step system is used with all bacterial groups (acidogenic, acetogenic and methanogenic) in each vessel or step (Fig. 5.3). Liquid digestate may be recycled from the second vessel to the first step. This recycle is a useful tool in the system as it allows for dilution of feedstock; it can also be used to balance the system (Thamsiriroj and Murphy, 2010). Generally the majority of the gas is produced in the first step of the two-step system. Thamsiriroj and Murphy (2010) found about 80% production of biogas in the first vessel when digesting grass silage.



5.4 (a) Vertical and (b) horizontal dry continuous processes (adapted from Nizami and Murphy, 2010).

5.5.4 Dry continuous reactors

Dry continuous reactors tend to be plug flow systems. In a plug flow system the substrate is introduced at one end and flows through the reactor as a plug without mixing. The fresh feedstock is inoculated by returning some effluent. A substrate concentration gradient exists between the inflow and outflow ends of the reactor and, theoretically, if the tube is long enough all the VS will be degraded on reaching the outlet. Thus, in theory, the effluent should contain lower concentrations of VFAs and yield higher removal efficiencies than from a completely mixed reactor operating at the same HRT. However in practice, friction from the walls, convection currents from heating systems and gas production cause mixing. These systems may be vertical or horizontal (Fig. 5.4).

5.6 Parasitic energy demand of process

The reactor configuration has a significant impact on the energy balance of the system. The next section continues the analysis from Box 5.1 and Box 5.2 on digestion of OFMSW. A dry continuous process is chosen with data provided by the technology provider, as described by Murphy and McCarthy (2005).

5.6.1 Thermal parasitic energy demand

The thermal parasitic demand for digestion of OFMSW is evaluated at 2.9% of the energy content of the biogas in Box 5.4. The higher the moisture content the higher the parasitic demand. If an external heat source is provided then the efficiency of combustion of that source will have an effect on the exact parasitic demand. If, for example, natural gas is combusted at 85% thermal efficiency, then the parasitic thermal demands rises by the

Box 5.4 Parasitic demand of dry continuous digestion of OFMSW at thermophilic temperature*Thermal demand*

Specific heat capacity of water 4.184 kJ/kg/°C

Water content of feedstock 700 kg/t

Thermal demand of feedstock $4.184 \text{ kJ/kg/}^\circ\text{C} \times 0.7 \text{ water/solids} = 2.93 \text{ kJ/kg OFMSW/}^\circ\text{C}$

Temperature rise 45°C ($15\text{--}60^\circ\text{C}$) = $131 \text{ kJ/kg} = 36.6 \text{ kWh/t OFMSW}$

200 m_n^3 biogas generated per tonne of OFMSW or 4.5 GJ/t OFMSW

Parasitic thermal demand $131 \text{ MJ/t} = 131/4500 = 2.9\%$ of energy in biogas

Electrical demand

Parasitic electrical demand of $85 \text{ kW}_e \text{ h/t}$ (Murphy and McCarthy, 2005) = 306 MJ/t

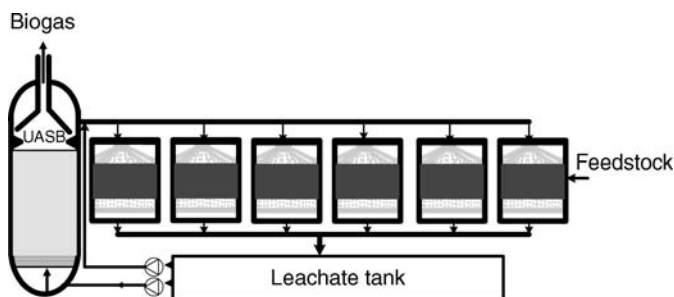
Parasitic electrical demand = $306/4500 = 6.8\%$ of energy in biogas

If electricity generated at $35\%\eta_e$ then demand = $306/(0.35) \times 4500 = 19\%$ of energy in biogas

reciprocal of 0.85, to 3.4%. Obviously the source of external heat source is important to the overall system. Thermal energy may be generated from fossil fuel combustion, biomass combustion or from combustion of the biogas itself. If biogas is used for combined heat and power production then the heat produced may be utilised to satisfy thermal demand. On the other hand, if biogas is upgraded to biomethane then the biogas may be considered too valuable to burn as a source of heat. Sustainability criteria may suggest combustion of biomass rather than fossil fuel to satisfy thermal demand.

5.6.2 Electrical parasitic energy demand

The electrical parasitic demand is 6.8% based on $85 \text{ kW}_e \text{ h/t}$; this is associated with the pretreatment, pumping and mixing of OFMSW in a dry digestion process (Murphy and McCarthy, 2005). The electrical demand is significantly less for a dry batch process where the waste is loaded and unloaded using standard diesel-fuelled equipment. Electricity in a small-scale combustion process is typically generated at an efficiency of approximately 35%. Thus, the parasitic electrical demand could rise to around 19% of the energy contained in the biogas.



5.5 Sequencing leach bed reactor with upflow anaerobic sludge bed (UASB) (adapted from Nizami and Murphy, 2011).

5.7 Laboratory analysis and scale up

5.7.1 Single-phase and two-phase systems

This section examines the effect of reactor configuration on the methane production for a given feedstock (in this case grass silage). High solid content feedstocks at commercial scale are typically digested in single-phase systems (all microbiological stages in one vessel). These may be a dry batch system (Fig. 5.2), a wet continuous system (Fig. 5.3) or a dry continuous system (Fig. 5.4). Rarely, if ever, are two-phase systems (such as in Fig. 5.5) employed at commercial scale. Within the scientific literature there are a number of descriptions of two-phase systems (Cirne *et al.*, 2007; Lehtomaki and Bjornsson, 2006; Yu *et al.*, 2002), but the authors have yet to encounter such a system at commercial scale. Potential scale up of two-phase systems to commercial facilities needs further research and development.

To examine differentiation of single- and two-phase systems, a series of laboratory experiments was undertaken comparing the same feedstock (grass silage cut from the same field at the same time) monodigested in different reactor configurations, as described by Thamsiriroj and Murphy (2010), Thamsiriroj and Murphy (2011), Nizami *et al.* (2011a), Nizami *et al.* (2011b) and Nizami and Murphy (2011). The grass silage was analysed (DS 30.66%; 92% of which VS; 19 MJ/kg VS; 1 kg of VS produces 1.4 kg COD). The feedstock was used in a two-step digestion process with recirculation of liquor (layout similar to Fig. 5.3(b)) and in a two-phase system (Fig. 5.5). The two-phase system was a sequencing-fed leach bed reactor (SLBR) complete with upflow anaerobic sludge blanket (UASB). The phases were separated. Hyrdolysis and acidogenesis took place in the leach beds; methanogenesis took place in the UASB reactor (Fig. 5.5).

Table 5.4 Comparison of one- and two-stage digestion of grass silage

	SLBR-UASB	CSTR
HRT (days)	30	50
CH ₄ content of biogas (%)	71	52
l CH ₄ /kg VS	341	451
VS destruction (%)	75	90
DS content of digestate (%)	10	5.6

Source: Nizami *et al.* (2011b).

5.7.2 Wet continuous digestion of grass silage

The two-step system (two reactors each with an effective volume of 300 l) when optimised produced 451 l CH₄/kg VS with a 50-day retention time and an organic loading rate of 2 kg VS/m³/day (Thamsirirotj and Murphy, 2011). The methane content averaged 52%. The digestate had a solids content of 5.6%. Volatile solids destruction averaged 90%.

5.7.3 Two-phase digestion of grass silage

This system comprised six separate leach beds. These were each loaded sequentially with 3.5 kg of baled grass silage in a 5-day cycle: day 0, feed bed 1; day 5, feed bed 2; day 10, feed bed 3, and so on till day 30 when leach bed 1 was emptied and re-fed (Nizami and Murphy, 2011). Liquor was sprinkled over the leach beds; this was collected in a leachate tank. From the leachate tank the liquor was either recirculated over the beds or pumped through the UASB (30 l volume) before recirculation over the beds (Nizami and Murphy, 2011).

When optimised, 75% of volatiles were destroyed in the leach beds producing 1.4 kg COD/kg VS. Each kilogramme COD destroyed generates 350 l CH₄ (Sperling and Chernicharo, 2005). The UASB achieved 93% removal efficiency (Nizami and Murphy, 2011). Thus, methane production in theory should be (0.75 destruction of volatiles \times 1.4 kg COD/kg VS \times 350 l CH₄/kg VS destroyed \times 0.93 =) 342 l CH₄/kg VS. The methane, as measured above the UASB, averaged 342 l CH₄/kg VS. The digestate had a DS content of about 10%.

5.7.4 Comparison of systems

A choice exists for the designer in crop digestion (Table 5.4). A traditional wet system (in this case a two-step system with recirculation of liquor) or an innovative system (with associated risk?) employing two phases. The two-phase system has 60% of the retention time of the wet system, has a

digestate high in solids content that may be suitable as a feedstock for a biorefinery concept, has a higher methane content in the biogas, but produces 24% less methane (Nizami *et al.*, 2011b).

5.8 Modelling and optimisation of anaerobic digestion

5.8.1 Modelling of anaerobic digesters

Mathematical modelling allows use of data from experiments or actual operating digesters to simulate operating conditions under different loading conditions. The model takes into account the specific configuration of the digesters.

- A vertical dry continuous reactor with mixing of feedstock and digestate before pumping to the top of the reactor as described by De Baere (2010) (and as indicated in Fig. 5.4(a)) is modelled as a series of CSTRs with the effluent from one reactor acting as the influent for the next reactor.
- A horizontal dry continuous reactor (Fig. 5.4(b)) with an axial paddle stirrer is modelled in a similar fashion to the vertical reactor but allows for bifurcation and recycling of part of the bacterial biomass (Zaher and Chen, 2006).
- A wet continuous reactor (Fig. 5.3(a)) with biogas recirculation under pressure to provide mixing can be modelled as a single CSTR (Zaher and Chen, 2006).

This section examines Anaerobic Digestion Model No 1 (ADM1) (developed by Batstone *et al.* (2002) under the International Water Association (IWA) Task Group for Mathematical Modelling of Anaerobic Digestion Processes) as applied to the CSTR (Fig. 5.3(a)). The model has been widely used by researchers to investigate anaerobic digestion of various feedstocks and digester configurations.

5.8.2 Description of ADM1

ADM1 is a mathematical model that simulates the behaviour of different particulate (solid) and soluble (liquid) components within an anaerobic digester. The model deals with anaerobic digestion in three dimensions: processes, components and time. Input feedstock is assumed to be a composite particulate material that can be broken down into different substrate components through processes taking place within the digester (Fig. 5.1). Conservation of mass is applied. The processes are categorised into two main processes – biochemical and physico-chemical processes (Batstone *et al.*, 2002).

The biochemical processes involve disintegration, hydrolysis, acidogenesis, acetogenesis and methanogenesis. Initially, the feedstock is disintegrated into carbohydrates, proteins and lipids, which are subsequently hydrolysed (Thamsiriroj and Murphy, 2011). A first-order function is used to describe disintegration and hydrolysis and also the decay rate of microbes (Thamsiriroj and Murphy, 2011). The Monod function models the growth rate of microbes coupled with the uptake rate of monomers. Inhibition terms are also added to the Monod function to allow the simulation of reduced uptake rate caused by inhibitory effects.

The physico-chemical processes include liquid–liquid processes (i.e. ion association/dissociation) and liquid–gas processes (Batstone *et al.*, 2002; Thamsiriroj and Murphy, 2011). pH is a liquid–liquid process; it is determined in the ADM1 model by balancing cationic and anionic charges that are present in the digester. Production of methane, carbon dioxide and hydrogen is a liquid–gas process.

5.8.3 Mathematical model in ADM1

The digester model is built on a mass conservation basis. At steady state, the balance of mass input and output for an ideal CSTR can be described by a set of algebraic equations such as equation 5.4 (Nauman, 2002).

$$q_{in}c_{in,i} + V_{liq} \sum_j \rho_j v_{i,j} = q_{out}c_{liq,i} \quad [5.4]$$

where q_{in} and q_{out} are volumetric inflow and outflow rate (m^3/day); $c_{in,i}$ and $c_{liq,i}$ are inflow and outflow concentration of component i ($\text{kg COD}/\text{m}^3$); the outflow concentration also represents the concentration within the digester; V_{liq} is the digester fermenting volume (m^3); ρ_j is the kinetic rate function of process j ($\text{kg COD}/\text{m}^3/\text{day}$); and $v_{i,j}$ is the stoichiometric coefficient of component i in process j .

However, since the conditions in an anaerobic digester are not usually in steady state, algebraic equations are replaced by differential equations. In the model, three categories of differential equations are formed and solved simultaneously. These categories include: liquid phase equations, acid–base equations and gas phase equations.

Liquid phase equations

Component i (c_i) can be divided into soluble (liquid form, S_i) and particulate (solid form, X_i) components. In total, there are 24 components in the liquid phase, 12 soluble and 12 particulate components (Table 5.5), combining in 19 different processes ($j = 1$ –19) as shown in Table 5.6.

The differential equations describing these components are given by

Table 5.5 Components in liquid phase

Soluble	Particulate
$S_{liq,1}$ Monosaccharides (S_{su})	$X_{liq,13}$ Composites (X_c)
$S_{liq,2}$ Amino acids (S_{aa})	$X_{liq,14}$ Carbohydrates (X_{ch})
$S_{liq,3}$ Long-chain fatty acids (S_{fa})	$X_{liq,15}$ Proteins (X_{pr})
$S_{liq,4}$ Total valerate (S_{va})	$X_{liq,16}$ Lipids (X_{li})
$S_{liq,5}$ Total butyrate (S_{bu})	$X_{liq,17}$ Sugar degraders (X_{su})
$S_{liq,6}$ Total propionate (S_{pro})	$X_{liq,18}$ Amino acid degraders (X_{aa})
$S_{liq,7}$ Total acetate (S_{ac})	$X_{liq,19}$ Long-chain fatty acid degraders (X_{fa})
$S_{liq,8}$ Hydrogen (S_{h_2})	$X_{liq,20}$ Valerate and butyrate degraders (X_{c_4})
$S_{liq,9}$ Methane (S_{ch_4})	$X_{liq,21}$ Propionate degraders (X_{pro})
$S_{liq,10}$ Inorganic carbon (S_{ic})	$X_{liq,22}$ Acetate degraders (X_{ac})
$S_{liq,11}$ Inorganic nitrogen (S_{in})	$X_{liq,23}$ Hydrogen degraders (X_{h_2})
$S_{liq,12}$ Soluble inerts (S_i)	$X_{liq,24}$ Particulate inerts (X_i)

Source: Adapted from Batstone *et al.* (2002).

Table 5.6 Processes in liquid phase

$j = 1$ Disintegration	$j = 10$ Uptake of propionate
$j = 2$ Hydrolysis of carbohydrates	$j = 11$ Uptake of acetate
$j = 3$ Hydrolysis of proteins	$j = 12$ Uptake of hydrogen
$j = 4$ Hydrolysis of lipids	$j = 13$ Decay of sugar degraders
$j = 5$ Uptake of sugars	$j = 14$ Decay of amino acid degraders
$j = 6$ Uptake of amino acids	$j = 15$ Decay of LCFA degraders
$j = 7$ Uptake of LCFA	$j = 16$ Decay of valerate and butyrate degraders
$j = 8$ Uptake of valerate	$j = 17$ Decay of propionate degraders
$j = 9$ Uptake of butyrate	$j = 18$ Decay of acetate degraders
	$j = 19$ Decay of hydrogen degraders

Source: Adapted from Batstone *et al.* (2002).

equations 5.5 and 5.6 (Batstone *et al.*, 2002). In some cases, the average residence time of particulate components in the digester is longer than hydraulic retention time (HRT) due to inhomogeneous mixing. It is thus useful to include the term $t_{res,X}$ into the equation as shown for particulate components.

$$\frac{dS_{liq,i}}{dt} = \frac{q_{liq}}{V_{liq}} (S_{in,i} - S_{liq,i}) + \sum_{j=1-19} \rho_j v_{ij}; \quad i = 1-12 \quad [5.5]$$

$$\frac{dX_{liq,i}}{dt} = \frac{q_{liq} X_{in,i}}{V_{liq}} - \frac{X_{liq,i}}{t_{res,X} + V_{liq}/q_{liq}} + \sum_{j=1-19} \rho_j v_{ij}; \quad i = 13-24 \quad [5.6]$$

where $S_{in,i}$ and $S_{liq,i}$ are inflow and outflow concentration of soluble component i ; $X_{in,i}$ and $X_{liq,i}$ are inflow and outflow concentration of particulate component i ; q_{liq} is volumetric flow rate assuming $q_{in} = q_{out}$

(m³/day); and $t_{\text{res},X}$ is the solid retention time (SRT) exceeding HRT (day), i.e. if $t_{\text{res},X} = 0$, $\text{SRT} = \text{HRT}$ (Thamsiroj and Murphy, 2011).

Acid–base equations

The pH of the fermenting liquor can be simulated using six physicochemical processes that describe the acid–base equilibrium of $\text{CO}_2/\text{HCO}_3^-$, $\text{NH}_4^+/\text{NH}_3$, HAc/Ac^- (acetate), HPr/Pr^- (propionate), HBu/Bu^- (butyrate) and HVa/Va^- (valerate). If strong bases or acids are present in the feed influent or if biocarbonate is added, the model allows them to be accounted through the components $S_{\text{cat}+}$ and $S_{\text{an}-}$ representing cations and anions respectively. Equations 5.7 and 5.8 are required for determining pH (Thamsiroj and Murphy, 2011).

$$\frac{dS_{\text{liq},i}}{dt} = \frac{q_{\text{liq}}}{V_{\text{liq}}} (S_{\text{in},i} - S_{\text{liq},i}); \quad i = 25\text{--}26(\text{cations and anions}) \quad [5.7]$$

$$\frac{dS_{\text{H}^+}}{dt} = \frac{\left[\frac{dS_{\text{an}^-}}{dt} + \frac{K_{\text{a,IN}}}{(K_{\text{a,IN}} + S_{\text{H}^+})} \frac{dS_{\text{IN}}}{dt} + \frac{K_{\text{a,CO}_2}}{(K_{\text{a,CO}_2} + S_{\text{H}^+})} \frac{dS_{\text{IC}}}{dt} + \left(\frac{1}{64}\right) \frac{K_{\text{a,ac}}}{(K_{\text{a,ac}} + S_{\text{H}^+})} \frac{dS_{\text{ac}}}{dt} + \left(\frac{1}{12}\right) \frac{K_{\text{a,pro}}}{(K_{\text{a,pro}} + S_{\text{H}^+})} \frac{dS_{\text{pro}}}{dt} + \left(\frac{1}{160}\right) \frac{K_{\text{a,bu}}}{(K_{\text{a,bu}} + S_{\text{H}^+})} \frac{dS_{\text{bu}}}{dt} + \left(\frac{1}{208}\right) \frac{K_{\text{a,va}}}{(K_{\text{a,va}} + S_{\text{H}^+})} \frac{dS_{\text{va}}}{dt} - \frac{dS_{\text{cat}^+}}{dt} - \frac{dS_{\text{an}^-}}{dt} \right]}{\left[1 + \frac{K_{\text{a,IN}} S_{\text{IN}}}{(K_{\text{a,IN}} + S_{\text{H}^+})^2} + \frac{K_{\text{a,CO}_2} S_{\text{IC}}}{(K_{\text{a,CO}_2} + S_{\text{H}^+})^2} + \left(\frac{1}{64}\right) \frac{K_{\text{a,ac}} S_{\text{ac}}}{(K_{\text{a,ac}} + S_{\text{H}^+})^2} + \left(\frac{1}{12}\right) \frac{K_{\text{a,pro}} S_{\text{pro}}}{(K_{\text{a,pro}} + S_{\text{H}^+})^2} + \left(\frac{1}{160}\right) \frac{K_{\text{a,bu}} S_{\text{bu}}}{(K_{\text{a,bu}} + S_{\text{H}^+})^2} + \left(\frac{1}{208}\right) \frac{K_{\text{a,va}} S_{\text{va}}}{(K_{\text{a,va}} + S_{\text{H}^+})^2} + \frac{K_{\text{w}}}{(S_{\text{H}^+})^2} \right]} \quad [5.8]$$

where $\text{pH} = \log_{10}(S_{\text{H}^+})$; S_{H^+} is the concentration of hydrogen ions (kmole H^+/m^3); dS_i/dt is rate of change of component i as defined in equation 5.5; $K_{\text{a},i}$ is the equilibrium constant of component i (kmole/ m^3) and K_{w} is the equilibrium coefficient of H_2O (kmole/ m^3).

Gas phase equations

Biogas considered in the ADM1 model is composed of methane, carbon dioxide and hydrogen. The transformation of biogas from liquid to gaseous form is considered in equation 5.9 based on the ideal gas law (Batstone *et al.*, 2002)

$$\frac{dS_{\text{gas},i}}{dt} = -\frac{S_{\text{gas},i} q_{\text{gas}}}{V_{\text{gas}}} + \rho_{T,i} \frac{V_{\text{liq}}}{V_{\text{gas}}}; \quad i = \text{H}_2, \text{CH}_4 \text{ and } \text{CO}_2 \quad [5.9]$$

where $S_{\text{gas},i}$ is the concentration of gas component i (H_2 and CH_4 in $\text{kg COD}/\text{m}^3$ and CO_2 in $\text{kmole C}/\text{m}^3$); V_{gas} is digester headspace (m^3); q_{gas} is

biogas flow rate (m^3/day), defined by

$$q_{\text{gas}} = \frac{RT}{P_{\text{gas}} - P_{\text{gas,H}_2\text{O}}} V_{\text{liq}} \left(\frac{\rho_{\text{T,H}_2}}{16} + \frac{\rho_{\text{T,CH}_4}}{64} + \rho_{\text{T,CO}_2} \right)$$

P_{gas} is total headspace pressure (bar), defined by $P_{\text{gas}} = p_{\text{gas,H}_2} + p_{\text{gas,CH}_4} + p_{\text{gasCO}_2} + p_{\text{gas,H}_2\text{O}}$; $p_{\text{gas,H}_2\text{O}}$ is water vapour pressure (bar); $\rho_{\text{T},i}$ is kinetic gas transfer rate of gas component i ($\text{kg COD}/\text{m}^3/\text{day}$); R is the gas law constant ($\text{bar m}^3/\text{kmole}/\text{K}$); and T is operating temperature (K).

Combining equations 5.5 to 5.9 yields a set of 30 differential equations in total for the simulation of a single CSTR digester system. More details on the construction of these differential equations can be found in Rosen and Jeppsson (2006). In the case where the system includes for recirculation of digestate as input together with the feedstock, equations 5.10 and 5.11 are added to the model

$$S_{\text{in},i} = S_{\text{feed},i}f_{\text{feed}} + [S_{\text{liq},i}(1 - f_{\text{feed}})]; \quad i = 1-12, 25-26 \quad [5.10]$$

$$X_{\text{in},i} = X_{\text{feed},i}f_{\text{feed}} + [X_{\text{liq},i}(1 - f_{\text{feed}})]; \quad i = 13-24 \quad [5.11]$$

where $S_{\text{feed},i}$ and $X_{\text{feed},i}$ are the concentrations of component i in feedstock input and f_{feed} is the fraction of feedstock input to total inflow.

5.8.4 Initial conditions and digester input

Solving differential equations requires values for initial conditions. In the case of a CSTR the initial conditions are the conditions of the components within the digester. There are 30 variables included in the model: 12 liquid and 12 particulate variables (as described in Table 5.5); 3 ion state variables (cations, anions and hydrogen ions); and 3 gas phase variables (methane, carbon dioxide and hydrogen). It may not be practical to determine the initial condition of each variable based on laboratory measurement. A more effective approach is to allow an initial period of digester operation to serve as model calibration. Samples of initial digester content are required for the measurement of dry solids (DS) and volatile solids (VS) content. The DS are assumed to be composite particulate material (X_c), which are further subdivided into inerts (ash), carbohydrates, proteins and lipids. Inert material is the ash content calculated from the difference between %DS and %VS. The fraction of carbohydrates, proteins and lipids can be measured or initially assumed. The simulation results in the early part of the calibration period will not be accurate. However, accuracy will improve as the contents of the digester are gradually replaced by new input feed. As the characteristics of the input feed are sufficiently known, the simulation in the later part of calibration period will gradually increase in accuracy when

compared to the actual data. For the input feed characteristics, it may not be necessary to measure the content of all components if the feedstock is dominated by composite material. For example, in monodigestion of grass silage, the model input may be assumed as a composite material because grass silage comprises approximately only 10% of readily soluble components (such as soluble sugars and VFAs); 90% of the feedstock is comprised of particulate components (Thamsiriroj and Murphy, 2011). The particulate feedstock is converted into soluble components during the anaerobic process, which narrows the gap between simulation and actual observation of such components. However, if the input feed is low in solids content but high in soluble COD such as industrial wastewater, then a more detailed analysis of feed characteristics is required to enable an accurate simulation.

5.8.5 Optimisation of anaerobic digestion using computer models

The behaviour of an anaerobic digester is complex and highly dynamic and involves a series of processes that are interrelated. Failure of an individual process can result in failure of the entire system. The stability of an anaerobic digester depends on many factors such as feedstock characteristics, organic loading rate, retention time, reactor operating conditions and reactor configuration (dry or wet, batch or continuous, number of connected digesters, separation of phases, recirculation of digestate). Modelling allows variation of one factor while the others are fixed and thus the effect of an individual factor on the digester performance can be simulated. For example, a model created by Lai *et al.* (2009) was used to predict the optimal concentrations of bicarbonate initially added to produce high methane yields in a batch reactor digesting OFMSW; Thamsiriroj and Murphy (2011) applied the ADM1 to simulate the behaviour of a two-stage CSTR system digesting grass silage in which they found that recirculation of digestate can limit the build-up of total VFAs, resulting in long-term stable operation. The simulation of many individual factors can help to illustrate the optimal conditions in which the design and operation will be most effective. Modelling can also be used to identify a process that becomes rate limiting and eventually leads to digester failure. A modelling study by Thamsiriroj *et al.* (2011) on grass monodigestion suggested that acetogenesis is a critical step that can become rate limiting in long-term operation due to the scarcity of micronutrients. This would concur with findings by Banks (2011) that selenium and cobalt are essential micronutrients for food waste digestion.

5.9 Conclusions and future trends

The bacterial processes involved in anaerobic digestion are understood, but complex. The interplay of the complexity is best monitored using modelling packages such as ADM1. Modelling will allow more aggressive loading of reactor systems and lead to more economical design.

Continuously stirred reactors are ubiquitous; two-step systems are the norm. Innovation has taken place in commercial reactors; this is particularly the case for high solid content feedstocks that can now be digested in wet digesters with recirculation of liquid digestate, sequentially fed dry batch reactors with recirculation of liquor in a closed loop and dry continuous reactors. However, the two-phase systems described in the scientific literature (leach beds coupled with high rate digesters) are rarely encountered in the commercial world. It is expected that these systems will become more prevalent as the literature becomes more mainstream. It is also the authors' opinion that the two-phase system will become associated with green biorefinery systems.

Sustainability concepts that have been applied to liquid biofuel systems in the EU Renewable Energy Directive (European Commission, 2009) will be applied to bioenergy systems. The energy balance of the process will become a more crucial design issue and may lead to the ultimate choice of reactor system.

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Optimisation of biogas yields from anaerobic digestion by feedstock type

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Abstract: This chapter considers optimisation of a biogas plant from a number of different perspectives. These include creating ideal conditions for microbes, maximising the overall net energy yield, and achieving the full range of environmental benefits of anaerobic digestion (AD). Basic concepts of digester loading and hydraulic retention time are explored and the relationship between them demonstrated for different feedstock types. The limitations on the performance of a digester are explained in terms of metabolic capacity and examples are given of how these can be minimised in practice. The importance of digester operating conditions is examined, including the role of temperature, macronutrients and micronutrients, and mixing and mass transfer. The need for pre-treatment and the advantages of co-digestion of feedstocks to balance nutrient requirements are discussed. Selection of digester type is also considered in relation to the feedstock. The chapter concludes with three case studies to illustrate optimisation of the AD process to meet different goals.

Key words: optimisation, feedstock selection, pre-treatment, metabolic capacity, specific methane yield, volumetric productivity.

6.1 Introduction

This chapter considers optimisation of biogas yield from the anaerobic digestion (AD) process by looking at some of the factors that may influence the performance of the plant with respect to its functionality as a waste treatment process, as a source of renewable energy and to the role it may have in environmental protection. These factors are considered in relation to

the process microbiology and biochemistry, the process engineering design and the feedstock properties. Three scenarios are used to show how simple one-component optimisation might be applied within a more complex multi-component system, where the desired outcomes may be policy driven and require optimisation of more than a single component.

6.2 Defining optimisation

To address the issue of optimisation of biogas yield relative to the feedstock type, it is first necessary to consider what we mean by the term optimisation, not only in the scientific sense but also in the wider context of AD as an economically and environmentally sustainable technology for waste management and renewable energy production.

In the simplest sense, optimisation is the process carried out when we have a range of parameters that can be controlled and a single variable that we want to maximise or minimise: in the case of AD for energy production this might be the biogas yield or, in the case of AD for waste management, the quantity of residual waste solids for disposal. There is no lack of laboratory studies applying this approach in experiments designed to provide a basis for large-scale operating protocols. More commonly, however, there are two or more parameters for which we want to achieve optimum values; for example, we may want the highest possible biogas production from the smallest possible digester, or the maximum energy yield with the minimum operating costs. There may be multiple desirable outcomes and a range of possible input parameters that could satisfy them. In AD it is very rare that we formulate precisely what we want in a way that can be expressed and solved mathematically. Very often we do not really know enough about the systems that we are trying to design and operate, or the factors that influence them, to have a high degree of control. The word optimisation is therefore usually used in a fairly loose and non-mathematical sense to mean something that gives us a result that is better than at least some of the alternatives and in a range that we are happy with. In this chapter, we will consider a few examples both of the simplest type of optimisation in which we explore a range of parameters affecting one outcome and of the more complex issues that have to be considered in multi-parameter optimisation. The simple examples will be set in the context of the more complex problems and different scenarios will be used for illustration.

As an example, consider the following two scenarios. Firstly, the waste manager who receives daily deliveries of a waste feedstock and wants to maximise the throughput of the plant in terms of wet tonnage per unit of capital investment. The manager also has to show that the stability of the final product meets regulatory requirements for reuse, recovery or disposal and of course he wants the maximum biogas yield. Secondly, the energy

farmer who grows and harvests a fodder crop once a year, for which he receives no gate fee, and it costs him to produce this feedstock which he has to store all year in order to feed the digester daily. In this case, the size of the digester in relation to throughput may not be critical and a more important consideration is that the process is capable of extracting the maximum amount of energy from the substrate, as this is the only source of income. In both cases, the plant owners wish to optimise the plant and in both it is likely to be on economic performance: in the first against throughput and gate fee income and in the second on exported energy. Even the second approach may not maximise overall energy recovery, as the focus will always be on the fraction of the energy output that generates the best economic return.

At a higher level, governments and international organisations may also be looking towards AD as a renewable energy source and see its value as a second-generation process in achieving this from waste. Some have also recognised that the process can give additional environmental benefits, for example in minimisation and offsetting of greenhouse gas emissions, through the use of digestate as a fossil fertiliser substitute and by improving nutrient management, and as a means of facilitating more environmentally sustainable management of animal manures and slurries through co-digestion. This type of environmental optimisation, however, requires not only consideration of the types, sizes and distributions of digestion plants but also more coherent regional or national planning, a suitable regulatory regime and careful selection of policy drivers and penalties needed to incentivise the preferred outcome.

6.3 Basic definitions and concepts

6.3.1 Biogas and methane yield

A particular substrate has a maximum theoretical specific methane yield based on its carbon content, and it is not possible to exceed this however the plant is designed and operated. The basis for this theoretical value was first explored by Symons and Buswell (1933) and is discussed in Chapter 5. In practice, however, the theoretical value cannot be achieved, as a proportion of the carbon along with the energy gained from the catabolic reaction is used by the microorganisms themselves in maintenance and growth of their own biomass. A proportion of the carbon may also not be converted because it is not anaerobically biodegradable, being protected from microbial attack because of its chemical structure or physical location (e.g. within a lignin bundle). The maximum specific methane yield of a substrate, expressed as $\text{m}^3 \text{CH}_4 \text{kg}^{-1} \text{VS}$, can, however, be experimentally determined in a biochemical methane potential (BMP) test (see Chapter 3).

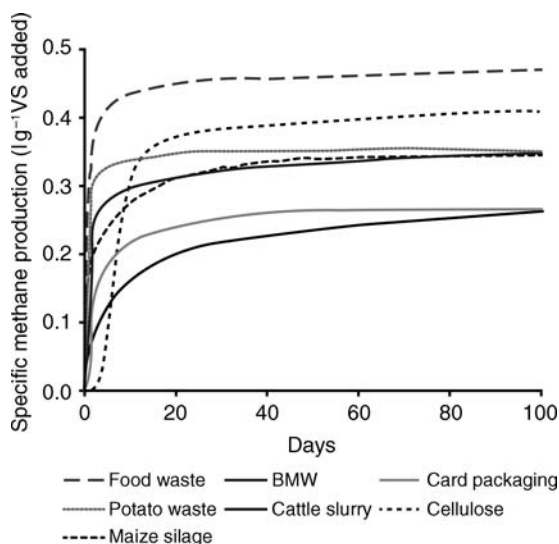
This is usually carried out under the most favourable conditions of temperature, inoculum type, nutrient balance and test duration (Angelidaki *et al.*, 2009). In practice, the BMP or maximum specific methane yield may not be achieved in a continuously or semi-continuously operated digester for a number of reasons: in a mixed system such as a stirred tank reactor, a proportion of the substrate will bypass the system; the nominal average retention time of the digester may be insufficient for degradation to proceed to completion; or the balance of nutrients and minerals may be unsatisfactory to maintain an active anaerobic consortium.

There are examples where almost all of the maximum specific methane yield of the substrate is achieved and these relate primarily to substrates with rapid degradability or systems with a long retention time, or a combination of the two. Many of the new generation of energy crop digesters fed on maize silage achieve specific methane yields approaching the BMP value. On the other hand, a digester treating municipal wastewater biosolids or animal slurries is unlikely to achieve the BMP value if operated at an economic loading rate. This is because the degree of dilution of the substrate reduces the retention time to a point where more recalcitrant components of the substrate cannot be degraded.

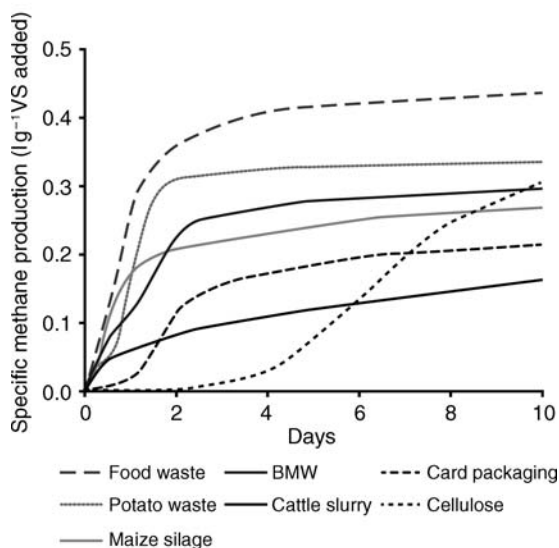
Examples of some BMP test results for selected substrates are shown in Fig. 6.1. As can be seen from the figure, the rates of reaction at which degradation occurs are variable, with substances like food waste breaking down rapidly while others (e.g. cattle slurry) have a much slower gas production rate. It is clear that the final BMP values vary considerably, from around $0.471 \text{ CH}_4 \text{ g}^{-1} \text{ VS added}$ for food waste to $0.261 \text{ CH}_4 \text{ g}^{-1} \text{ VS added}$ for cattle slurry and card packaging (Fig. 6.1(a)). The shapes of the gas production curves also differ quite markedly: substrates with a high proportion of fibre, such as cellulose and biodegradable municipal waste (BMW), show a distinct lag period lasting 1–4 days, which corresponds to the period needed for hydrolysis of the long-chain polymers before fermentation and methanogenesis can begin. The other substrates all showed a rapid initial rate of gas production which, in the case of food waste, continued until almost all of the methane potential had been realised. In the case of cattle slurry, this slowed quite rapidly and the final methane potential had still not been achieved after 100 days, while maize silage and potato waste lay between these two extremes. In all cases, the data shown were taken from BMP tests carried out in stirred mesophilic digesters with inoculum taken from the same municipal wastewater biosolids digester, and carried out using the method described in Banks and Zhang (2010).

Gas production curves of the type shown in Fig. 6.1 are sometimes modelled using a simple first-order rate equation

$$Y = Y_{\max}(1 - e^{-kt}) \quad [6.1]$$



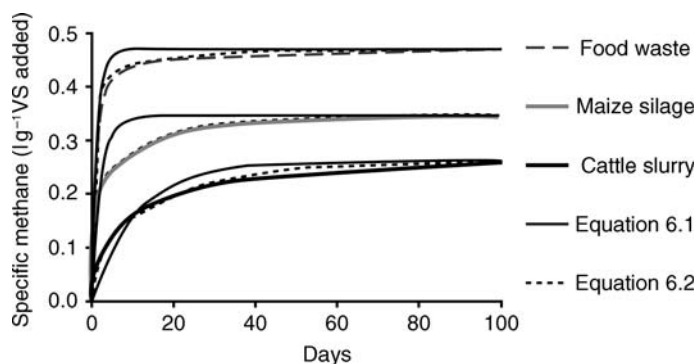
(a)



(b)

6.1 BMP test results for selected substrates. (a) Full result for a 100-day test. (b) First 10 days of 100-day test.

where Y is the cumulative methane yield at time t , Y_{\max} is the ultimate methane yield and k is the first-order rate constant. In many cases, however, this gives only moderately good results: this is in part because the substrates are heterogeneous and consist of both rapidly and more slowly degrading



6.2 Kinetic models for selected substrates.

Table 6.1 Kinetic parameters from BMP modelling

Parameter values	Food waste		Maize silage		Cattle slurry	
	Eq. 6.1	Eq. 6.2	Eq. 6.1	Eq. 6.2	Eq. 6.1	Eq. 6.2
$Y_{\max}(\text{l CH}_4 \text{ g}^{-1} \text{ VS added})$	0.470	0.470	0.345	0.345	0.260	0.260
P	1	0.88	1	0.60	1	0.33
k or k_1	0.73	1.02	0.44	1.50	0.09	0.50
k_2	0	0.06	0	0.07	0	0.05
R^2	0.9874	0.9980	0.9703	0.9987	0.9911	0.9978

fractions. A better fit can be obtained by assuming that the gas production curve reflects these different rates and properties. Methane production is therefore given by

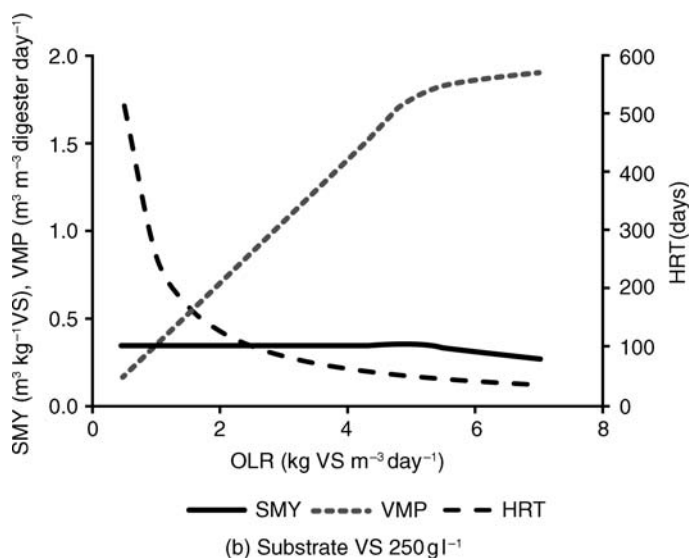
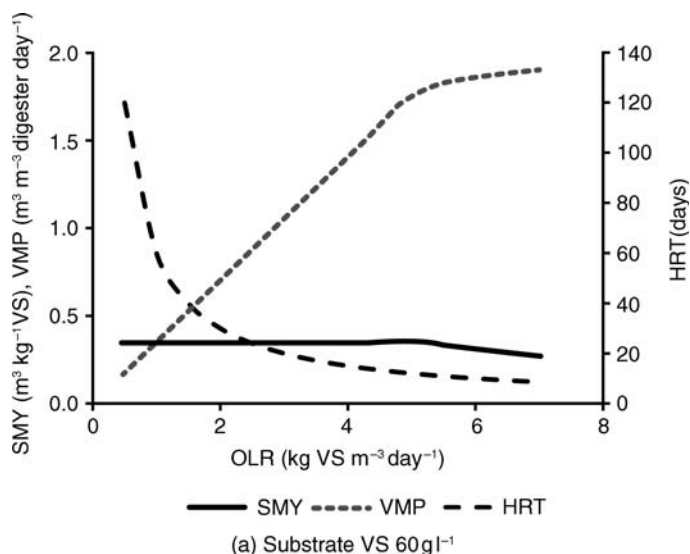
$$Y = Y_{\max} [1 - Pe^{-k_1 t} - (1 - P)e^{-k_2 t}] \quad [6.2]$$

where Y is the cumulative methane yield at time t , Y_{\max} is the ultimate methane yield, k_1 is the first-order rate constant for the proportion of readily degradable material, k_2 is the first-order rate constant for the proportion of less readily degradable material and P is the proportion of readily degradable material. Results for food waste, maize silage and cattle slurry are shown in Fig. 6.2 and the kinetic coefficients for equations 6.1 and 6.2 are given in Table 6.1. In each case it can be seen that equation 6.2 provides a better fit. The P values of 0.88, 0.60 and 0.33 reflect the relative proportions of readily degradable material in food waste, maize silage and cattle slurry respectively. The decay constant k_2 is similar in all three cases, but the k_1 values are different. As expected k_1 is higher for food waste than for cattle slurry as the latter has effectively already undergone a digestion process. Maize has the highest value of all, reflecting the presence of fermentation products from the ensiling process that are almost immediately available for uptake by the methanogenic population.

6.3.2 Biogas and methane productivity

Although the specific methane yield of a substrate is a function of the substrate itself, the methane productivity is dependent on the rate at which it is produced and, importantly, on the digester volume that produces it. Productivity is therefore often expressed as $\text{m}^3 \text{CH}_4 \text{m}^{-3} \text{ digester day}^{-1}$. From a kinetic perspective, the most important factors determining this in a continuous digestion system are the food-to-biomass ratio and the net specific growth rate of the biomass. In a simple single-pass digester without solids recycle, the net specific growth rate is equal to the dilution rate, which is the reciprocal of the hydraulic retention time (HRT). The food-to-mass ratio, also known as the biomass organic loading rate (OLR), is difficult to determine and is therefore often expressed simply on a volumetric basis, using either volatile solids (VS) or chemical oxygen demand (COD) as the measure of organic matter. Of these parameters, the OLR is paramount in determining the methane productivity provided that the HRT is not reduced to a point where the methanogens are washed out.

The effect of increasing the OLR on a digester of the continuous stirred tank reactor (CSTR) design is shown in Fig. 6.3. The specific methane yield (SMY) remains relatively constant as the loading is increased, resulting in a linear increase in the volumetric methane production (VMP). During this time, the HRT decreases because the volume of material added must increase in order to satisfy the organic load, assuming that the feedstock VS content remains constant. In the hypothetical example shown in Fig. 6.3(a), which is based on a slurry input with a VS of 60 g l^{-1} , the HRT would reach the 'safe limit value' of 12 days at an OLR of $5 \text{ kg VS m}^{-3} \text{ day}^{-1}$. Higher loadings would start to wash out the methanogens, with a fall in specific methane yield as both contact period and quantity of biomass are reducing. When the feedstock VS content is increased as in Fig. 6.3(b), the only parameter that changes is the HRT. In this case a safe limit value for HRT is not reached even when the highest loading is applied and, in fact for this VS content, the loading could theoretically be increased to $20 \text{ kg VS m}^{-3} \text{ day}^{-1}$ before the HRT reaches the critical 12-day value. Yet the hypothetical curve still shows a drop in specific methane yield and volumetric methane production at about the same loading: this is based on typical empirical data, but depends on a number of factors discussed later in the chapter. What is certain is that the loading to a single-pass digester cannot be increased indefinitely as there comes a point when the metabolic capacity of the digester is reached; that is, the amount of biomass present can no longer consume all the food applied – in this respect bacteria are not much different to humans! Little information is available as to what this maximum loading rate is, because to produce a real graph for even a single substrate in place of the hypothetical Fig. 6.3 represents a large experimental effort even at



6.3 Relationship between organic loading rate (OLR) and specific methane yield (SMY), volumetric methane production (VMP) and hydraulic retention time (HRT) for two different substrate VS contents but with the same SMY. (Note different scales on right-hand vertical axes.) (a) Substrate VS 60 g L⁻¹. (b) Substrate VS 250 g L⁻¹.

laboratory scale. In both of the cases shown in Fig. 6.3, the point of inflection on the SMY curve represents a loading above which some of the methane potential of the substrate is lost, and for maximum methane

productivity the digester should work as close to this as possible. Most commercial digesters tend to work within empirically established ranges that do not necessarily represent the point of inflection of the VMP line. There are, however, other factors that may affect the loading that can be applied: for example, the ability to separate solids from the liquor in the digestate or even the ability to mix the digester itself may limit the operation before optimal biogas production is achieved. Commercial digesters may also work above the point of inflection if their income stream is mainly dominated by gate fees rather than by energy production.

Up to now, the OLR has been expressed in terms of $\text{kg VS m}^{-3} \text{ day}^{-1}$ even though some of these VS may not be bio-available because of their molecular structure or physical position in the substrate. For comparison of the performance of anaerobic digesters processing different feedstocks the OLR is not necessarily a good parameter and it would be more logical to express loading as $\text{kg BMP m}^{-3} \text{ day}^{-1}$. For example, it has often been said that the so-called ‘dry’ digestion systems can accept higher organic loadings than ‘wet’ systems (Guendouz *et al.*, 2010; Weiland, 2010); yet, in order to maintain functionality, dry systems often rely on a proportion of the feedstock applied not degrading but acting as a support matrix, to allow the use of solids handling equipment rather than pumps. More feedstock is added, but more undegraded material is removed, and performance in terms of $\text{kg VS destroyed m}^{-3} \text{ day}^{-1}$ may be similar. It is likely that the metabolic capacity of both types of digester is equal and ultimately this biological capacity is what determines the process efficiency.

6.4 Overcoming limitation as a result of hydraulic retention time (HRT)

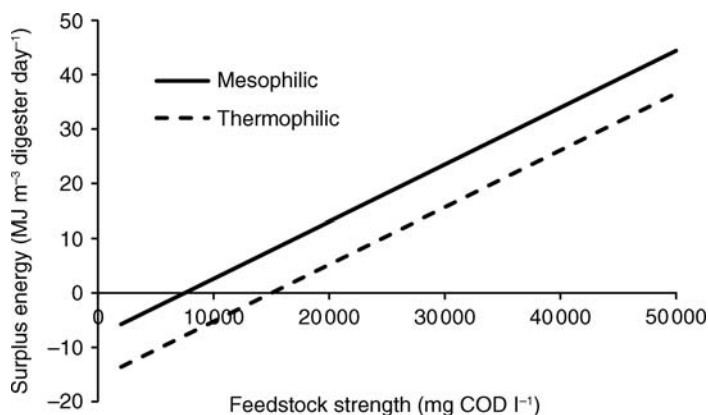
Where the maximum loading that can be applied to a digester is due to the safe limit value for the HRT, then the optimisation strategy for the digester might be to increase the VS content of the substrate, for example by dewatering if the substrate is a slurry. Where the substrate is a liquid effluent then the digester design has to be changed to allow retention of the anaerobic biomass and prevent washout. This can be achieved with designs such as the upflow anaerobic sludge blanket (UASB) digester (Seghezzo *et al.*, 1998) or one of the many retained biomass designs aimed at industrial wastewater treatment applications (e.g. Liao *et al.*, 2006; Chernicharo 2007; Singh and Prerna, 2009; see also Chapter 5).

6.5 Increasing the metabolic capacity of a digester

Where the maximum load on a digester is defined by its metabolic capacity then improvement in the volumetric methane productivity could be gained by increasing that metabolic capacity. This concept applies mainly to digesters that are receiving substrate at a relatively high concentration, although there are cases where the performance of slurry digesters can also be improved when the limitation is shown not to be the HRT. Factors that might be considered and which could contribute to increasing the metabolic capacity of a digester are operating temperature, availability of macro-nutrients, micronutrient status and aspects of digester design.

6.5.1 Operating temperature

Temperature has a strong effect on a range of kinetic parameters, including the maximum specific growth rate of microorganisms, the half-saturation constant, the growth yield and the decay rate. The maximum rates at which microorganisms can utilise substrates are thus strongly temperature dependent, with methanogens more sensitive than hydrolytic or acidogenic bacteria. Methanogenic organisms can grow over a very wide temperature range (Madigan *et al.*, 2010) but well-established optima exist at around 35–40°C (mesophilic) and around 55°C (thermophilic) and these temperature ranges are therefore the most common ones for full-scale operation. Some methanogens are known that have higher optimal growth temperatures (e.g. Zeikus and Wolee, 1972; Lauerer *et al.*, 1986; Miller *et al.*, 1988; Kurr *et al.*, 1991) but these extreme thermophiles have not so far been exploited on a commercial scale. Depending on the substrate, the rate of methane generation in thermophilic systems may be 25–50% higher than in mesophilic systems, allowing shorter retention times. At the same time, thermophilic systems are more susceptible to variations in operating and environmental conditions, and are more likely to accumulate volatile fatty acids (VFA). When optimising an AD system for net energy production, the additional energy required to raise and maintain feedstock and digester contents at this temperature must also be taken into account. Figure 6.4 shows an example of the calculated surplus energy available from the digestion of a fixed daily volume (100 m³) of feedstocks with different COD concentrations entering a mesophilic (35°C) or thermophilic (55°C) digester with a minimum 12-day retention time at an influent and ambient temperature of 15°C, assuming that all of the COD is converted to methane and taking into account heat transfer losses from a typical insulated digester (Salter and Banks, 2009). In terms of optimising the process, the increase in volumetric production that could be obtained by operating at thermophilic temperature needs to be compared with the additional energy consumed in



6.4 Calculated energy surplus from digestion of different strength feedstocks at a 12-day HRT after raising feedstock temperature from 15°C to mesophilic (35°C) and thermophilic (55°C) temperatures.

the process if it is necessary to raise the feedstock temperature. While the rate of methane generation in thermophilic systems may be higher than in mesophilic systems, it is unlikely that operating at higher temperature will increase the specific methane yield of a given substrate and this can only be determined on a case-by-case basis, for example in dual-temperature BMP studies with acclimatised inoculums.

Alternatives considered to optimise the benefits of different temperatures ranges include temperature-phased anaerobic digestion (TPAD) systems, with a thermophilic first stage (acidogenic reactor) followed by a mesophilic methanogenic reactor to combine high rates of solids degradation and pathogen reduction with improved process stability and effluent quality (Lv *et al.*, 2010). For maximum gas production, temperature stability is also very important. Variations of the order of only one or two degrees have been reported to have an adverse effect (WEF, 1998).

6.5.2 Macronutrients

Biomass is mainly composed of C, H, N, O and S, and these elements must be present in the substrate if microbial growth is to occur. In anaerobic systems most of the C, H and O are converted to CH₄ and CO₂, whereas any N and S not incorporated into new biomass is rapidly reduced to ammonia and sulphides in either soluble or gaseous form. Both ammonia and sulphides are toxic to methanogens and once a critical concentration is reached a portion of the metabolic capacity will be inhibited, in extreme cases leading to total failure of the digester. It is usually easier to overcome potential problems associated with these two compounds by restricting the

amount entering the digester as part of the feed. For this reason an optimal ratio between C/N is often referred to in the scientific literature and values quoted are almost always in the range 20–30:1. Too little N is also potentially a problem as there is a minimum requirement for growth: values of C/N over 40 are likely to be insufficient, leading to restrictions in the growth of the microbial consortium and reduction in the metabolic capacity. Nitrogen in the form of ammonia also provides an important buffering component. This is well demonstrated in the digestion of abattoir and food wastes, where high ammonia concentrations allow stable digester operation with high VFA; in contrast, digestion of low-nitrogen products such as paper wastes can be problematic, as relatively small changes in VFA concentration can lead to drastic swings in pH. Too much N, however, will lead to ammonia concentrations known to be inhibitory to methanogens. Surprisingly, despite the number of reported studies that have looked at ammonia inhibition, it is still difficult to give exact values for the concentration at which it becomes toxic (see also Chapter 5). This is partly due to the fact that ammonia in digesters exists in the form of the more toxic free ammonia and less toxic ammonium ions, with the equilibrium strongly dependent on pH and temperature. A number of equations have been put forward to describe this relationship, such as that proposed by Østergaard and quoted by Hansen *et al.* (1998)

$$\frac{\text{Free NH}_3}{\text{Total NH}_3} = \left(1 + \frac{10^{-\text{pH}}}{10^{-\left(0.09018 + \frac{2729.92}{T(\text{K})}\right)}} \right)^{-1}$$

where $T(\text{K})$ is the temperature in Kelvin.

It is now accepted that acetoclastic methanogens are more sensitive to ammonia inhibition than hydrogenotrophic methanogens (see Section 6.7.1), and the C/N ratio may therefore start to dictate the biochemical pathway through which methane can be formed. Based on the authors' experience in food waste digestion, acetoclastic methanogens are replaced by hydrogenotrophic at around 500 mg l^{-1} of free ammonia in both mesophilic and thermophilic systems. Phosphorus is also needed for cell growth and the requirements can usually be satisfied at a C/P ratio of 120. In some cases it may be necessary to supplement the feed to achieve this.

At the C/S ratio of ~600 that is required for microbial growth, it is unlikely that sulphur will become limiting for most feedstocks, but it may have an impact on metabolic capacity of the system. This is due firstly to the competition for acetate, a methane precursor, as an energy source by sulphate-reducing bacteria. These bacteria work at a higher redox potential than methanogens and can outcompete them for intermediate product energy sources. Secondly, soluble sulphides are themselves inhibitory to

methanogenic bacteria at concentrations of 100–150 mg S l⁻¹ (Speece, 1983). A further effect is that soluble sulphides can form complexes with trace elements to form insoluble sulphides; and for this reason iron is often added to the digester in the form of iron salts to reduce sulphur toxicity and improve microelement availability. Hydrogen sulphide can also be removed by micro-oxidation and precipitation of elemental sulphur. As H₂S is of concern to operators because of its corrosiveness, odour and toxicity to humans, H₂S removal may also be regarded as a process optimisation parameter.

6.5.3 Micronutrients

Micronutrients are essential to methanogenic consortia as they form part of the coenzymes used in many of the reactions leading to methane formation. If their supply is restricted, the capacity of the population to synthesise enzymes is likewise restricted, which in turn will compromise the metabolic capacity of the digester. Trace elements not only have to be present, but also need to be in a bio-available form. Any inadequacy either in trace elements or in their bio-availability will result in lower maximum loading rates and/or less efficient treatment. The build-up and persistence of VFA in digestate may be indicative of nutrient deficiency, but if bio-availability and the presence of nutrients is satisfactory then toxicity is an alternative that should be investigated.

Although iron was known to be stimulatory to AD, it was not until the 1980s that trace elements were found to be the missing factors needed to maintain activity in digesters fed on pure culture media. Nickel was the first identified, followed by cobalt, and the practical benefits of this were soon realised: in a survey of AD plants treating municipal wastewater biosolids, Speece (1988) noted that 8 out of 30 digestates tested showed increased rates of acetate utilisation and methane production when supplemented with Fe, Ni and Co. Since then, studies have consistently shown that the addition of trace elements can be beneficial to the digestion process for a wide range of feedstocks and digester types. Likewise, trace elements have been identified that are important in methanogenic metabolism as well as necessary for the process of acetogenesis. A summary of where these elements are used in different metabolic pathways is given in Table 6.2.

It is difficult to provide a trace element dosing guide to satisfy every eventuality, because trace elements form insoluble precipitates with sulphide, carbonate and phosphate. The elements may be kept soluble by chelation (combination with another molecule), but may bind strongly with the chelating agent forming complexes that again render them unavailable. Overdosing to try and overcome these limitations is not a good policy, as certain trace elements may be stimulatory at low concentrations but toxic at higher ones.

Table 6.2 Role of trace elements in acetogenic and methanogenic pathways

Trace element	Comment	Probable enzyme function	References
Iron	Present in methanogenic tissue in concentrations higher than any other metal. It plays numerous roles in anaerobic processes, primarily due to its extremely large reduction capacity. Iron may form sulphide precipitates, but may also promote excretion of extra-cellular polymers which can have a chelating action	Clusters with Ni and S to make subunits of enzymes such as hydrogenase, acetyl-CoA synthase, carbon monoxide dehydrogenase (CODH) and formyl MF dehydrogenase	Brock <i>et al.</i> , 1984 Kayhanian and Rich, 1995 Schattauer <i>et al.</i> , 2011 Somitsch, 2007
Cobalt	Has been shown to be beneficial in many situations including methylotrophic conversion, and is also important to acetoclastic and hydrogenotrophic routes	Required for the synthesis of vitamin B12 which is essential in functioning of coenzyme M methylase. Essential for methyltransferase. In acetogenesis, essential in CODH	Burgess <i>et al.</i> , 1999 Kayhanian and Rich, 1995 Kida <i>et al.</i> , 2001 Oleszkiewicz and Sharma, 1990 Schattauer <i>et al.</i> , 2011 Schonheit and Thauer, 1979 Somitsch, 2007.
Nickel	The nickel tetrapyrrole coenzyme F430 is known to bind to methyl-S-CoM reductase, which catalyses methane formation in both acetoclastic and hydrogenotrophic methanogens. F430 has been found in all known methanogens. In addition, carbon monoxide dehydrogenase (CODH) contains a nickel protein and is involved in acetogenic pathways for both methanogenic and sulphur-reducing bacteria. Ni stabilises DNA and RNA, and is a cofactor of urease	The role of Ni in methanogenesis is related to the following enzymes: methylreductase, hydrogenases and synthesis of F430. In acetogenesis, essential in carbon monoxide dehydrogenase CODH	Diekert <i>et al.</i> , 1981 Kayhanian and Rich, 1995 Kida <i>et al.</i> , 2001 Oleszkiewicz and Sharma, 1990 Somitsch, 2007 Speece, 1983 Thauer <i>et al.</i> , 1980 Zellner <i>et al.</i> , 1987
Selenium	Selenium is a component in several anaerobic prokaryotic enzymes and certain nucleic acids. Selenium-dependent	Formate dehydrogenase (FDH)	Kayhanian and Rich, 1995 Somitsch, 2007.

enzymes tend to be very reactive at neutral pH, have a low redox potential, and may help metabolise fatty acids. It forms part of the amino acid selenocysteine, known as the 21st genetically encoded amino acid

Molybdenum	Mo is a co-factor of various flavinuous enzymes; involved in nitrogen fixation in methanosarcina	FDH	Oleszkiewicz and Sharma, 1990 Schattauer <i>et al.</i> , 2011 Scherer, 1988 Somitsch, 2007. Kayhanian and Rich, 1995
Tungsten	Tungsten is a component of the formate dehydrogenase (FDH) enzyme. It is possible that tungsten may aid the metabolism of CO ₂ and H ₂ , in a manner similar to nickel	FDH	
Zinc and copper	Zinc and copper are present in relatively large concentrations in many methanogens. They can stimulate cell growth and are co-factors of RNA- and DNA polymerase. Not yet proven to be stimulatory to methane production	It may be part of FDH, super dimutase (SODM) and hydrogenase	Burgess <i>et al.</i> , 1999 Kayhanian and Rich, 1995 Kirby <i>et al.</i> , 1981 Oleszkiewicz and Sharma, 1990 Schattauer <i>et al.</i> , 2011.
Magnesium and manganese	Not yet proven to be stimulatory to methane production	Mn stabilises methyltransferase in methanogens and is often interchangeable with Mg in kinase reactions	Burgess <i>et al.</i> , 1999 Schattauer <i>et al.</i> , 2011

6.5.4 Mixing and mass transfer

Much early work in the 1950s on improving the AD process focused on heating and mixing the digester, increasing feedstock solids content and reducing the HRT. Laboratory and field experience at that time suggested that continuous mixing of the digester contents was required for successful operation. Even today, there is considerable debate in the literature as to whether mixing should be continuous or intermittent, by mechanical means or gas recirculation (Karim *et al.*, 2005); and there are several reports where mixing has been shown to slow down or reduce biogas production (Stroot *et al.*, 2001; Kaparaju *et al.*, 2008). There is still general agreement, however, that some mixing is necessary for a high rate of reaction.

Mixing helps to prevent stratification, temperature gradients, deposition of solids and scum, and crust formation. In doing this it maintains physical, chemical and biological uniformity in the digester and minimises short circuiting in CSTR designs. From a biological perspective, mixing systems provide active contact between the biomass and the substrate, distribute the feedstock effectively and, in a CSTR, dilute inhibitory substances.

In large-scale commercial systems possibly one of the biggest impacts associated with mixing, or the lack of it, is the build-up of inert high-density mineral materials (grit) in the base of the digester. This effectively reduces the size of the digestion tank, increases the organic loading and reduces the retention time – all factors that could adversely affect both the specific methane yield and the volumetric methane production if the digester is working close to its metabolic or hydraulic limits. Mixing is an energy-intensive process and consumes a proportion of the energy produced: an efficient mixing system for a CSTR should therefore aim to maintain all solids in suspension with the minimum energy input. The types of mixing systems and their relative merits are discussed in Chapter 8.

In dry high-solids digestion where reactors often have plug flow characteristics or may be operated in batch mode, mixing within the reactor itself is not normally applied but there is a high degree of mixing of fresh feedstock with inoculum at the start of the process to ensure good contact with the substrate. These reactors tend to be used with feedstocks that have a high fibre content, where a close association between substrate and degrading organisms through the formation of cellulosomes (Shoham *et al.*, 1999; Schwarz, 2001) may be important for species such as *Clostridium*, which are common fermentative agents in anaerobic systems.

Close association between different microorganisms is also important where syntrophy is an essential part of the metabolic pathway (Speece *et al.*, 2006). In these circumstances it has been suggested that mixing may adversely affect productivity and alternatives such as low or intermittent mixing and biomass retention systems may be preferable.

6.6 Matching feedstocks and digester type

6.6.1 Effect of pre-treatments on energy conversion

Pre-treatments are discussed in Chapter 4 but, as with selection of a suitable temperature range, from the viewpoint of process optimisation it is essential to consider both inputs and outputs. When dealing with energy crops or other feedstocks that have a production cost associated with them, many processes that apparently improve the specific methane yield per kilogramme VS may also reduce the overall mass of VS, thus giving little or no net gain in terms of yield in MJ tonne^{-1} or $\text{MJ ha}^{-1} \text{ year}^{-1}$: examples include loss of VS during ensilage, heat treatment or pre-aeration. Conversely, for a given digester capacity, increasing the rate of substrate conversion may improve volumetric gas production as the digester can process a larger volume of substrate in the same period even if the specific methane yield of the material is not increased.

6.6.2 Feedstock selection

Some feedstocks are difficult or unsuitable for mono-digestion because of their unfavourable C/N ratios or high lipid content: examples include abattoir wastes, fats and oils, and paper. In these circumstances, co-digestion is the best approach to resolve any imbalance and improve volumetric methane productivity: examples include the co-digestion of slaughterhouse wastes with animal slurries or municipal solid wastes and the addition of whey or glycerol (biodiesel by-product) to the digestion of livestock manures (Alvarez and Lidén, 2008; Kavacik and Topaloglu, 2010; Astals *et al.*, 2011). Feedstock selection or blending should also be considered as a means of optimising other aspects of performance. The physical characteristics of the digestate and in particular its dewaterability may have a significant effect on the overall process energy balance: wastes such as sugar beet pulp are often extremely difficult to dewater without chemical addition and centrifugation (Brooks *et al.*, 2008), giving the operator a choice between the energy cost of transporting large volumes of digestate versus that of processing the material. In some cases the chemical composition of feedstocks can result in precipitation of struvite (an insoluble salt of magnesium phosphate and ammonia) in the digestion plant, leading to blockages, physical damage and heat transfer losses; dense inert materials such as grit and stones in the original feedstock can have a similar effect and effective upstream pre-treatment is required to protect the system. The issue of final digestate quality is also a major factor determining feedstock selection. This is discussed in more detail in Chapter 12 but, in general, high-quality source-segregated materials should not be downgraded

by co-digestion with mixed-waste feedstocks that are potential sources of contamination because this reduces the value of the product and limits disposal options.

6.6.3 Digester type

From a process engineering point of view, optimisation could be regarded as finding a balance between the energy and raw materials required to operate the process against the output energy and added value of the digestate. It may also involve designing the process to meet the particular characteristics of the feedstock in terms of its energy density, solids content and biodegradability. Process engineering optimisation can also be interpreted in economic terms as minimising the cost of the technical equipment and ongoing operational costs relative to the return on investment. There are now many different plant design concepts to choose from, which have been variously catalogued under headings such as wet, dry, single phase, two phase, leach bed, complete mix, plug flow. Further information on these can be found in Chapter 5 with detailed accounts in texts such as those by Mata-Alvarez (2003) for solid wastes and Chernicharo (2007) for high-rate anaerobic wastewater treatment processes.

Although there are many aspirations in the scientific literature for the development of faster, smaller and more efficient digestion plants, ultimately the conversion of carbon substrate to methane gas is a biological function and the key limitations will therefore remain with the rate of hydrolysis for solid substrates and the growth rate of methanogens for liquid substrates. The latter can be overcome to a large extent by high rate systems with biomass retention and the former, to a lesser extent, by designing reactors to achieve more effective hydrolysis incorporating mechanical, chemical or biological pre-treatment systems. At the present time, 90% of reactors for digestion of solid substrates, sludges and slurries are vertically mounted CSTR-type digesters operating at mesophilic temperatures, as this type of reactor suits many of the currently available feedstocks. In cases where the feedstock has a high proportion of anaerobically non-degradable fibre with a low moisture content (e.g. municipal solid wastes), high solids 'dry' digestion systems offer an effective alternative and the low water content may also allow efficient operation at thermophilic temperatures, fulfilling the requirement for pasteurisation when used in plug flow mode. CSTR designs will always result in a proportion of bypass and where this is undesirable, for example in energy crop digestion, having primary and secondary digesters in series has been shown to maximise specific methane yield (Weiland, 2010).

6.7 Case studies

Three case studies are now presented to show how the anaerobic process can be optimised for different purposes. The examples have been chosen to illustrate how the process can be optimised to

- meet the metabolic needs of the anaerobic consortium
- obtain the best overall energy yield within defined system boundaries
- maximise overall environmental benefits.

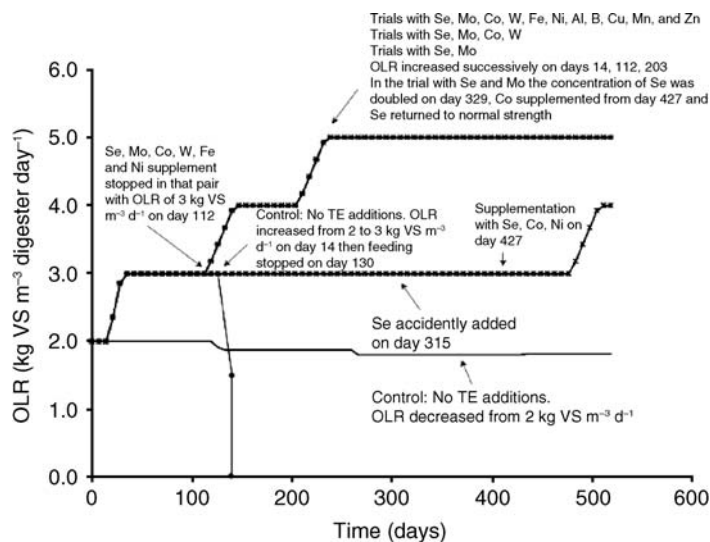
6.7.1 Case study 1. Optimising the volumetric methane production in food waste digestion

Food wastes and residues from food processing and animal slaughter are attractive feedstocks because of their high biogas potential, but AD of substrates with a high nitrogen content has always posed difficulties because of the build-up of ammonia to inhibitory concentrations. This case study shows how the digestion of source-segregated food waste has been optimised by increasing the metabolic capacity of the digester, through stimulating the more ammonia-tolerant hydrogenotrophic methanogens by selective trace element addition. Early studies (Banks *et al.*, 2008; Climenhaga and Banks, 2008) showed that mesophilic digestion of food waste could be achieved at moderate loadings but with an accumulation of VFA. Although undesirable for operational reasons, this did not result in a significant reduction in biogas production because the system was strongly buffered by ammonia, giving a pH greater than 7.8. The first full-scale treatment plant built in the UK to treat source-segregated domestic food waste also showed similar symptoms of VFA build-up, and the loading in this case was restricted to around $2 \text{ kg VS m}^{-3} \text{ day}^{-1}$ (Banks *et al.*, 2011). During these and other studies, a pattern was identified in which food waste digesters first accumulated acetic acid which reached a peak then declined, followed by a longer term accumulation of propionic acid. The timespan over which these changes occur depends on the process loading, but typically it was more than a year before the accumulation of acid products overcame the digester buffering capacity, leading to process failure. A theory was put forward to explain this (Banks and Zhang, 2010): the peak in acetic acid was a consequence of inhibition of the acetoclastic methanogens as the ammonia concentration reached a threshold value (Karakashev *et al.*, 2006; Schnurer and Nordberg, 2008). The subsequent decline in acetic acid, despite a continuing rise in ammonia concentrations, and its stabilisation at a low value were considered to indicate a shift in the dominant methanogenic activity from acetoclastic to hydrogenotrophic. The non-reversible accumulation of propionic acid was thought to occur due to deficiencies in the

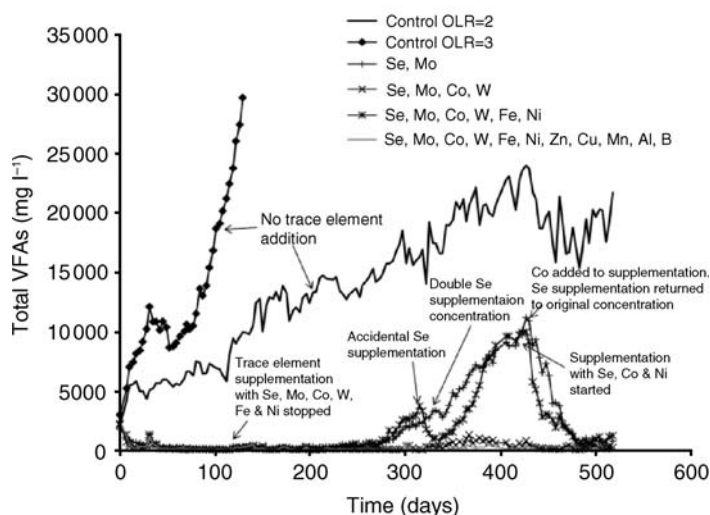
trace elements required for synthesis of the enzymes needed in syntrophic hydrogenotrophic methane production (see Chapter 5). In particular, selenium (Se) was thought to be important because of its role as a co-factor in formate dehydrogenase for formate oxidation (Böck, 2006). Accumulation of formate, a breakdown product of propionic acid, had been reported as possibly triggering feedback inhibition in propionic acid oxidation (Dong *et al.*, 1994).

A series of batch and semi-continuous tests was undertaken at laboratory scale to determine the effects of trace element addition in these high-ammonia food waste digesters (Banks *et al.*, 2012). Initial batch screening tests showed that addition of selenium could stimulate the breakdown of propionic acid in digestate from acclimated digesters operating at high ammonia concentrations. These batch experiments were followed by an extended semi-continuous digestion study in which trace elements (TEs) were tested singly and in combination against controls without TE supplementation at different OLRs (Fig. 6.5(a)). As expected, the control digesters without TE supplementation showed a slow accumulation of VFA over the study period and, in order to maintain biogas production, it was necessary to limit the loading to $1.6 \text{ kg VS m}^{-3} \text{ day}^{-1}$ (Fig. 6.5(b)). An increase in loading from 2 to $3 \text{ kg VS m}^{-3} \text{ day}^{-1}$ led to a rapid increase in VFA, resulting in acidification and digester failure. In digesters supplemented with TE combinations that included selenium, it was possible sequentially to raise the loading from 2 to 3, 4 and $5 \text{ kg VS m}^{-3} \text{ day}^{-1}$ at low VFA concentrations, and with a small increase in specific methane yield relative to the unsupplemented control at $1.6 \text{ kg VS m}^{-3} \text{ day}^{-1}$.

The digesters supplemented only with selenium began to show signs of VFA accumulation at a loading of $5 \text{ kg VS m}^{-3} \text{ day}^{-1}$, and at this point it was found that the addition of cobalt (Co) was necessary to reduce the VFA concentration and maintain stable digestion. The microbial population structure was confirmed using fluorescent in situ hybridisation (FISH) techniques to show that only hydrogenotrophic methanogens were present: later work using a ^{14}C radio-labelling technique has confirmed this as the route to methane production, with a complete lack of acetoclastic activity. The interpretation of these results in terms of the metabolic capacity of the digester is that there was a lack of the co-factors needed to allow expansion of the hydrogenotrophic population when the acetoclastic organisms became inhibited by increasing ammonia concentrations. The addition of selenium unblocked the metabolic pathway, allowing uneven carbon chain length VFA to be converted to acetate, hydrogen and CO_2 . Sufficient co-factors and TE were present in the food waste to allow acetate oxidation via the reverse Wood–Ljungdahl pathway until higher loadings were applied, when this pathway is thought to have become limited by the availability of cobalt, resulting in the acetate accumulation seen in Fig. 6.5(b) until cobalt

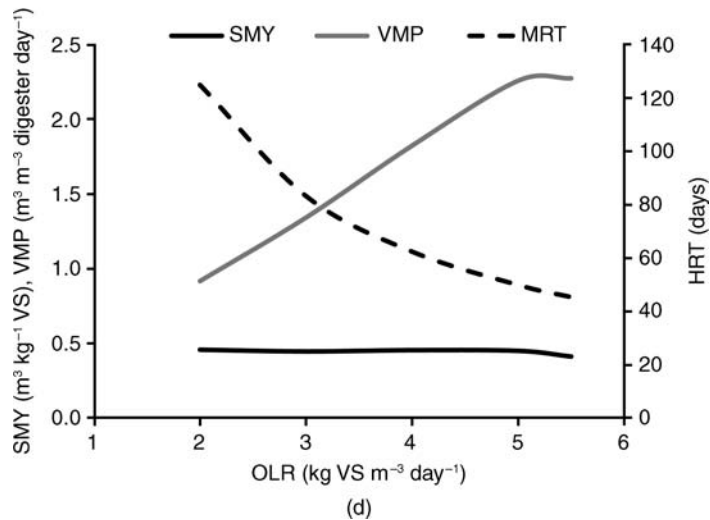
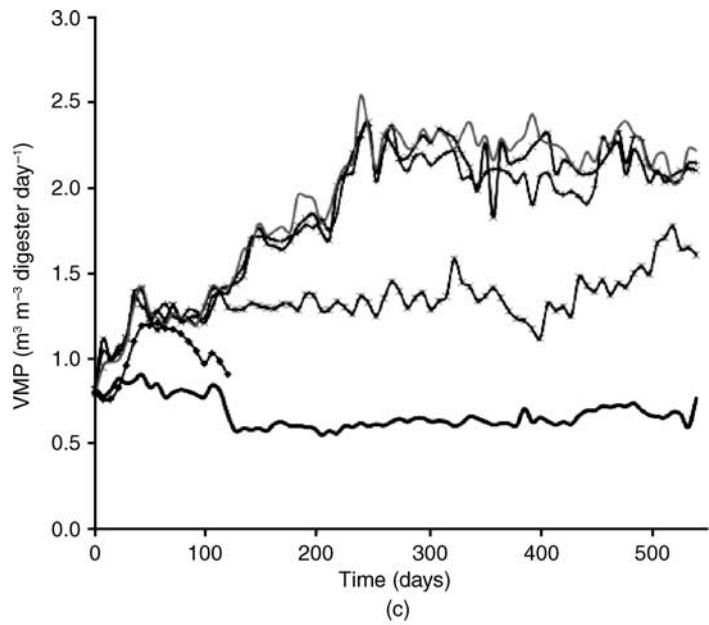


(a)



(b)

6.5 Food waste digestion trials undertaken to show effects of TE supplementation ((a) and (b) from Banks *et al.* (2012), courtesy of Elsevier. (a) Changes in OLR and TE supplementation during food waste digestion trail. (b) VFA concentrations at different OLR and TE supplementation. (c) VMP at different OLR and TE supplementation. (d) SMY, VMP and HRT at different OLR up to 5.5 kg VS m⁻³ digester day⁻¹.



6.5 (continued)

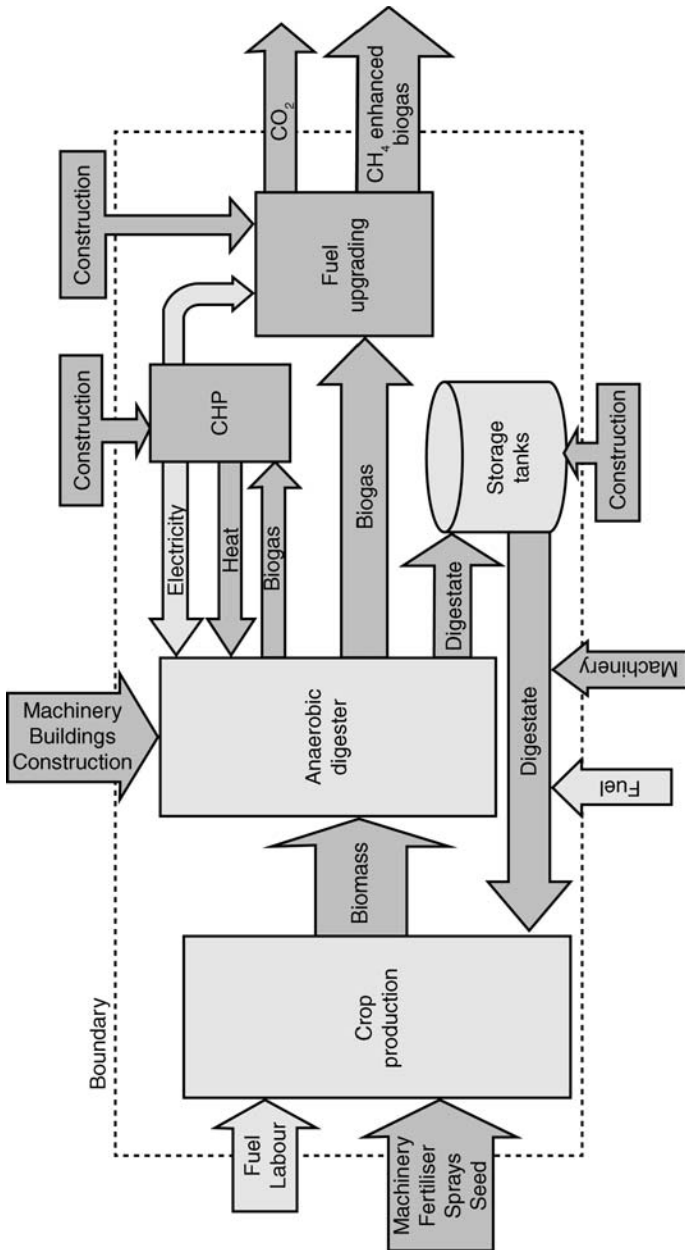
supplementation was added. The work also showed that the effects of TE addition were reversible by subsequent removal of the supplementation, and allowed determination of critical concentrations. These critical concentrations are load dependent, and it is clear that food waste digestion without supplementation could proceed at loadings of less than 2 kg VS m⁻³ day⁻¹. The addition of selenium and cobalt raised this to at least 5 kg VS m⁻³ day⁻¹

and improved the volumetric methane production from 0.9 to 2.3 kg VS m⁻³ digester day⁻¹ (Fig. 6.5(c)). This, however, is probably the limit of metabolic capacity for this digester, as can be seen in Fig. 6.5(d).

6.7.2 Case study 2. Optimising methane production from agricultural crops and residues

Renewable energy production using agricultural crops represents the largest expansion in AD technology in Europe (Weiland, 2010; Murphy *et al.*, 2011), with around 6000 plants currently in operation in Germany alone. Optimising methane production from these requires a whole systems analysis involving the types of crops that are grown, production costs, harvest time, the storage and pre-treatment of the crop, the inclusion and type of co-digestate, and resource recovery from the digestate product. The concept of optimisation can be taken still further to consider not just the methane yield for the biomass produced, but the energy balance for this, including direct and indirect energy usage as shown in Fig. 6.6 and further again in the form of a life cycle assessment.

Although it is useful to have a crop that has a high specific methane yield, it is more important that the methane yield per hectare of land under cultivation is maximised and that this yield is achieved using environmentally friendly crop rotations (Amon *et al.*, 2007a). One of the most common crops grown for digestion in central Europe is maize (*Zea mays* L.), but cereals such as wheat and triticale or grasses and legumes may be better suited to colder and wetter climatic conditions (Smyth *et al.*, 2009; Rincón *et al.*, 2010). Amon *et al.* (2007a) developed the methane energy value system for estimating the biogas production potential of crop materials. This is based on a compositional analysis of crude protein (XP), crude fat (XL) crude fibre (XF), cellulose (cel), hemi-cellulose (hem) and starch. The data are processed by regression analysis against experimental data from specific methane yield tests and coefficients are established that can then be used to calculate methane yields based on chemical composition. This technique has been used to evaluate a number of different crop varieties and also the impact of time of harvest on yield (Amon *et al.*, 2007b). The latter is particularly important as the specific methane yield of the biomass material may decline in late harvest even though the biomass yield per hectare increases: the crop is therefore optimally harvested when the product of specific methane yield and VS yield per hectare reaches a maximum. Amon *et al.* (2007a) suggested that the concept of the methane energy value model could be further extended for optimising methane yields from versatile crop rotations that integrate the production of food, feed, raw materials and energy.



6.6 Schematic illustration showing direct and indirect energy inputs used in calculating an energy balance for energy crop methane (based on Salter and Banks, 2009).

Animal slurries can also be a valuable part of the digestion mix but, because of their relatively low methane yield, the proportion used has to be carefully selected so as not to reduce the overall productivity of the digestion plant.

Micronutrients

Although the majority of farm-based digesters using energy crops as a feedstock co-digest with animal slurry, this is not always the case. Where there is mono-digestion of a crop then this may be at risk of a deficiency in micronutrients or an imbalance in macronutrients. In fact there are few mono-substrates that are likely to satisfy the full complement of micronutrients demanded by methanogens and syntrophic acetogens (Weiland, 2010; Demirel and Scherer, 2011). It is therefore not surprising that the supplementation of maize digesters with Fe, Co and Ni has improved biogas yields (Hinken *et al.*, 2008), while Se and Mo have also been found to be deficient (Lebuhn *et al.*, 2008). Optimum TE mixes for maize silage have been worked out in a series of trials using a synthetic model substrate (Pobeheim *et al.*, 2010, 2011). In some respects, however, it is unwise to base any dosing strategy on a fixed TE recipe without knowing the baseline concentrations in the digester as a result of TEs entering as part of the feedstock. TEs can be toxic as well as stimulatory to the anaerobic consortium and the concentration at one loading may be insufficient at a higher loading (see Section 6.7.1). Although it is possible to analyse the TE content of the digestate and then refer to guideline values, it is usually more sensible to follow the recommendations of Zitomer *et al.* (2008) and set up a simple series of test bottles to which individual TEs are added: an increase in biogas production of greater than two standard deviations in any variant will quickly indicate a probable TE deficiency.

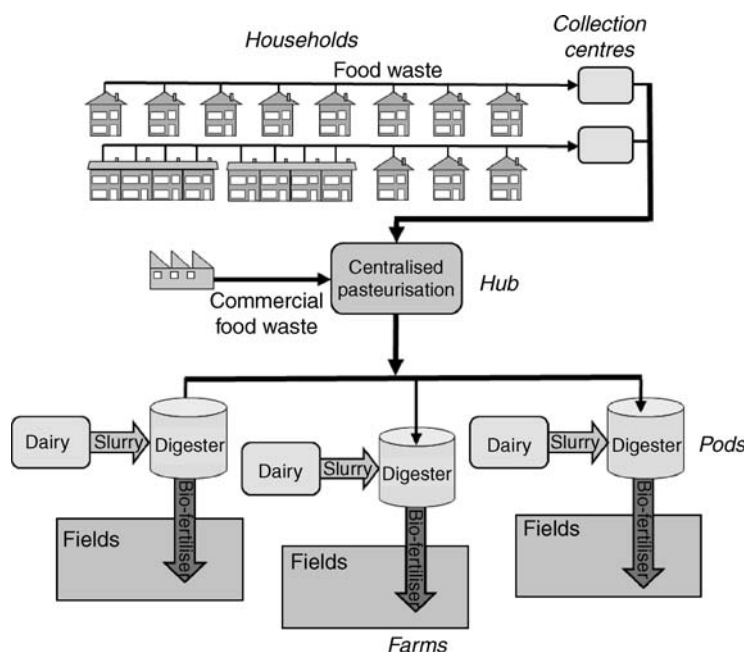
Trace element deficiencies are more likely to occur when crops or crop residues are digested without ruminant animal manure. Quite simply, farmers usually give their animals dietary supplements that contain the TEs necessary to stimulate the anaerobic consortia in the gut or rumen of the animals, and most of these elements pass out with the animal faeces (Sager, 2007). Slurry may not be seen as a good energy producer in AD processes, but it is certainly an excellent source of those elements that are likely to improve biogas production. Improvements in biogas production have also been reported in digestion plant treating grass-clover silage (Jarvis *et al.*, 1997) and sugar beet pulp due to the addition of cobalt. In our laboratory, as part of the EU 6th Framework project CROPGEN (www.cropgen.soton.ac.uk), digesters fed on a maize as a mono-substrate showed a requirement for cobalt at high loadings and this was supplemented as part of a TE mix (Gonzalez-Gil *et al.*, 2001).

6.7.3 Case study 3. Optimising methane production, reduction in greenhouse gas (GHG) emissions and nutrient recycling: closing the loop between urban and agricultural wastes

The European Commission estimates that about one third of the EU's 2020 target for renewable energy in transport could be met using biogas produced from biowaste, while around 2% of the overall EU renewable energy target could be met if all biowastes were converted to energy, with further economic gains from the associated recycling and waste prevention. To achieve this requires optimisation of methane production at a far larger scale than that of an individual plant or farm. The concept of centralised anaerobic digesters receiving and treating urban biowastes is rapidly becoming established, as is the practice of growing energy crops for farm-based digestion, both driven at least in part by renewable energy subsidies. Even with these subsidies, however, it is unlikely to be profitable to digest the 1.25 billion tonnes of animal slurries and manures generated in the EU, which are thought to contribute as much as 12–41% of total agricultural CH₄ emissions in most countries (Chadwick *et al.*, 2011). To optimise GHG capture and methane production from these requires co-digestion with energy-rich materials, and this could be economically sustainable if based on the polluter pays principle, reducing the level of renewable energy subsidy needed to incentivise such an action at a regional, national or international scale.

A successful example of this approach already exists in Denmark, where co-digestion has been practised since the 1970s (Raven and Gregersen, 2007). These schemes have co-digested 1.51 million tonnes per year of animal manure together with 340 000 tonnes per year of other biowastes, mainly from food manufacturing: this was achieved using a combination of 19 centralised co-digestion plants and 56 individual farm-scale plants (Al-Seadi, 2000).

To look at the feasibility of this approach using source-segregated domestic food waste as a co-substrate, a regional model was created for Hampshire in the UK in which the concept was evaluated against three objectives – maximising the methane production from urban and rural sources, minimising GHG emissions and closing the nutrient cycle by replacing the nutrients exported from dairy farms in their produce with imported urban-generated food waste. These three objectives were optimised on the basis of a nutrient management strategy in which no farm could import more nutrients than it exported, and neither imported nor farm-generated waste could be exported to other farms after digestion.



6.7 Schematic illustration of Hub and PoD system (Banks, 2011).

Farm-based digestion was chosen as the best option as most of the feedstock is generated on the farm and the digestate is spread on its land area. To minimise risks of the transmission of animal or plant disease the concept of a Hub and PoD (points of digestion) was developed (Fig. 6.7), where blending and sanitisation of the urban-generated waste feedstock takes place before export onto the farms. Although the digesters are located on farms they do not necessarily have to be operated by farmers, who could sub-contract this to a single operating company.

The model is based on

- an average food waste generation rate of 180 kg per household per year
- dairy cow slurry production of 19.3 tonnes per year
- recommended farm fertiliser application rates in a nitrogen vulnerable zone
- GHG emissions calculated using the IPCC methodology (IPCC, 2006)
- the values of Kongshaug (1998) for indirect energy use in fertiliser production
- biogas yields from co-digestion mixes taken from Banks and Zhang (2010)
- farm and herd sizes from the farm business survey (Defra, 2010)
- population statistics for the region

Table 6.3 Results for two Hub and PoD case study scenarios

	Scenario 1	Scenario 2
Dairy cows	300	300
Percentage housed	50	100
Slurry produced (tonnes year ⁻¹)	4454	8908
Cattle slurry: food waste in digester feed (wet weight basis)	1.8	2.9
Food waste required to replace N leaving the farm (tonnes year ⁻¹)	2453	3115
Digester loading rate (kg VS m ⁻³ day ⁻¹)	4	4
Digester capacity (including 10% gas space) (m ³)	540	788
Retention time (days)	26	22
Biogas (m ³ year ⁻¹)	394107	542090
Methane (m ³ year ⁻¹)	236464	325254
CHP (continuous electrical output) (kW)	99	136
Avoided CH ₄ emissions from manure (tonnes CO ₂ equivalent)	126.1	252.1
Avoided CO ₂ emissions by replacement of grid electricity	377.8	508.2
Avoided CO ₂ emissions by replacement of mineral fertiliser	136.3	173.1
Capital cost (£ kW ⁻¹)	4000	4000
Total capital cost (£)	396000	544000
Income from electricity (£ year ⁻¹)	139363	152915

- 60% capture rates for food waste
- centralised processing using waste heat at the county's three energy-from-waste plants
- distribution to farms in a 20 km radius in 25 -tonne loads.

Results for two scenarios are shown in Table 6.3, with a herd of 300 dairy cows, the average for a large dairy farm in Hampshire, either permanently housed or housed for 50% of the year.

Given that 76 434 tonnes of food waste is available in the region, this would be enough to supply 31 large farms based on their N requirements. In estimating the food waste import requirements in this way it was found that the proportions of nutrients in the cattle slurry and food waste did not completely match the crop requirements: the application of some P and K in mineral form is also required. The total methane generated on the farms is around 10 million m³ with around 29 ktonnes of CO₂ equivalent savings, but lower if the animals can graze freely in the summer months. The capital costs for a digester vary according to size: costs in the range £2000–7000 kW⁻¹ electricity installed have been suggested (MREC, 2008; Redman, 2008). These costs do not include connection to the national grid, planning or permitting, and the incomes shown are based on the current UK feed-in tariff scheme (£0.115 kWh⁻¹). Rolling such a scheme out across the UK to

combine 5 million tonnes of the UK's food waste with 40 million tonnes of animal slurry would allow the generation of 3 541 300 MWh of electricity: enough to supply 913 000 households and to save 1.8 million tonnes of CO₂ equivalent GHGs from grid-based electricity production.

This type of scheme is certainly in line with the recent EC communication on biowaste management (COM(2010)235) (European Commission, 2010) which highlights how AD can offer a means of realising a wide range of environmental benefits in a cost-effective manner as well as producing renewable energy. Optimisation of biogas yield in this case means taking into account the whole biomass resource available for AD and paying due attention to the capacity of the land base for receiving digestates.

6.8 Future trends

The rapid expansion of AD into new applications and feedstock types has presented many challenges. We are only just beginning to meet these by a better understanding of the process microbiology rather than by empirical, and often *ad hoc*, testing and guidelines. Improvements in process performance, volumetric biogas productivity and process stability are more likely to be achieved through understanding and manipulating the microbial catalyst and its environment than invention of some revolutionary new process. Although good engineering design will always pay dividends, it needs to be focused on translating advances in fundamental knowledge and applied science into workable solutions. We have to overcome the idea that an anaerobic digester is a rudimentary low-technology waste treatment and disposal system, and replace it with one of a process capable of delivering the multiple benefits of low-cost second-generation renewable energy production, a sustainable route to nutrient recycling and a means of abating GHG emissions.

Speece (1996) recalls 20 years (1960–1980) of lost opportunity in AD because we did not face the challenges but simply accepted that the process did not work with some substrates. We now have new tools such as gene sequencing and improved analytical methods that can provide us with the opportunity to explore the structure and function of the anaerobic community in more detail. It is unlikely that this will lead to 'revolutionary' new processes in the short term, but in the longer term as a more complete picture is built up it will help identify practical interventions to maximise the efficiency of the biochemical pathways and syntrophies in the process. We are only at the beginning in terms of the types of substrate being used: there is still the challenge of marine biomass, so we had better start learning about what drives halotolerant and halophilic methanogenic communities! There are large quantities of feedstock material with a relatively high proportion of poorly degradable carbon: the availability of this needs to be increased by

improved pre-treatments such as selective enzyme utilisation. Can the metabolic capacity and volumetric productivity of digesters be further increased by using supplements and co-factors to promote the activities of the anaerobic consortium or do we look to isolating and exploiting hitherto unrecognised methanogens that can work and grow faster in certain conditions, allowing higher loadings to be achieved without loss of conversion efficiency? The next 10 years may bring at least preliminary answers to many of these exciting questions, which will help to further optimise AD plant performance.

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Anaerobic digestion as a key technology for biomass valorization: contribution to the energy balance of biofuel chains

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Abstract: This chapter discusses the role of anaerobic digestion (AD) within biomass chains. It does so by firstly contextualizing the topic, highlighting the main possibilities opening up for different chains given the intrinsic advantages of AD. Next, a typology of AD cascades is set out and the possibilities of each cascade outlined following cascade chain theory. A methodology is then introduced for assessing the contributing role of AD to the energy balance of biomass chains. Finally, the framework is applied to three biofuel chains in Colombia. The implications of different chain configurations are discussed.

Key words: biomass chains, resource cascading, biofuels, anaerobic digestion, energy balance.

7.1 Introduction

For an expanding population living on a single planet, improving resource-use efficiency is a must. It was reported in 2008 that humanity's total ecological footprint was 1.3 planet Earths (WWF 2008). Prospects are not better today as the combined effect of population growth and consumption trends means that more resources, i.e. energy, land, water and nutrients, are demanded each day.

The finite quality and perceived short-term scarcity of fossil reserves, aggravated by existing geopolitical tension, has induced energy instability and high prices in recent years. Within this context, biomass has been rediscovered for its biofuel and chemical production potential as an alternative to fossil fuels. Both in the case of bioenergy and biorefineries, advantages in the valorization of biomass are found. Producing bioenergy from crops and agro residues is interesting for many reasons; perhaps the most attractive for investors being that some of the resulting biofuels such as bioethanol, biodiesel and biogas can be incorporated into the market using the energy infrastructure already in place. Other important advantages are its renewable character as long as vegetation is carefully managed, its relatively easier accessibility as compared with fossil fuels and the fact that it may be exploited using less capital-intensive technologies. In addition, the decrease in greenhouse gas (GHG) emissions coming from the use of fossil fuels can be a gain as they are replaced by carbon-neutral biofuels. The savings in GHG emissions could become an appealing economic incentive, particularly to less economically developed countries, as encouraged by the Clean Development Mechanism. Furthermore, processing biomass can provide a setting for industries to be brought into rural areas, which in turn can potentially create jobs and return money into rural systems and give the opportunity for local, regional and national energy self-sufficiency across the globe. Finally, in many cases, use of biomass can contribute to solve environmental problems, related for example to the inadequate management of waste, or undesirable biomass growth caused by eutrophication. However, the many advantages of biomass use for energy or chemicals production holds true only as long as the harvesting of solar energy via biomass is not performed at the expense of fossil fuel expenditure or inappropriate land use changes. In this sense, use of energy crops as main substrate should always be approached with caution, taking into consideration the expected impacts in the environmental and social spheres, because of the negative implications of intensive agricultural production and the possible competition with alternative biomass uses such as food, feed or soil conservation.

Within this context, anaerobic digestion (AD) is a very appealing alternative to add value to liquid and (semi) solid biomass. AD is considered a plain technology, converting chemically bound energy in organic (in) soluble matter into an 'easy-to-get' energy-rich gaseous end product (methane, CH₄) and a nutrient-rich semi-liquid stabilized by-product (i.e. digestate). Furthermore, AD is considered a very flexible technology, accepting a wide range of different types of substrates, producing an energy carrier with a very flexible end-use and with implementation scales varying from very small to very big. AD can be used to convert agricultural (by) products or energy crops into methane but it can also be part of different

biomass arrangements, giving an added value to residues in a rational way. The resulting methane can be directly used or can be upgraded to a higher quality gas suitable as vehicular fuel or for injection to the gas grid. Alternatively, it can be converted into electricity and heat in a combined heat and power (CHP) unit, or to heat or steam solely (IEA 2001, IEA 2005, Lindeboom *et al.* 2011). In this way, AD allows for closing energy, water and nutrient cycles at different scales, thereby resembling the ‘no-waste policy’ intrinsic to nature.

7.2 The role of anaerobic digestion in biomass chains

Anaerobic digestion as a technology has been around for a long time. Small-scale decentralized technologies such as the Chinese dome digester and the Indian floating dome are centuries old. In the industrialized world, AD has been majorly employed to treat wastewater and wet residues. Major technological applications of AD have been the treatment of sewage-derived sludges and, since the 1980s, the treatment of industrial wastewater (van Lier 2008; van Lier and Lubberding 2002). Other applications of the technology are the stabilization of (semi) solid wastes and slurries, crop residues and municipal solid waste (Mata-Alvarez *et al.* 2000).

The possible energy contribution from crops and manure for producing biogas was recognized in the 1980s. However, economically, electricity from other sources was still cheaper and this kept the concept from penetrating the market (Baier and Delavy 2005; DeBruyn and Don 2004). Recently, the potential of AD has been rediscovered as having a central role in delivering higher outputs from finite biomass resources, its final use being mainly energy applications. In the chemical industry, methane also plays a role, being a raw material for the manufacturing of methanol (CH_3OH), formaldehyde (CH_2O), nitromethane (CH_3NO_2), chloroform (CH_3Cl), carbon tetrachloride (CCl_4) and some freons. Furthermore, a cheap and efficient way of turning methane into liquid chemicals and fuels could free the chemical industry from its dependence on fossil fuels; this path is, however, still under development (e.g. Lindeboom *et al.* 2012).

Over recent years, and as the result of specific governmental incentives, the construction of bioreactors for biogas production having energy crops as (co) substrate has become a reality in countries like Germany, Austria and Sweden. In Germany, for example, it is estimated that in 1997 only 450 AD plants were functioning, while more than 6000 were producing biogas in 2010 (IEA 2011). There are more than 25 000 working biogas plants in China and it is estimated that more than 30 million biogas plants are working around the world (van Lier *et al.* 2011).

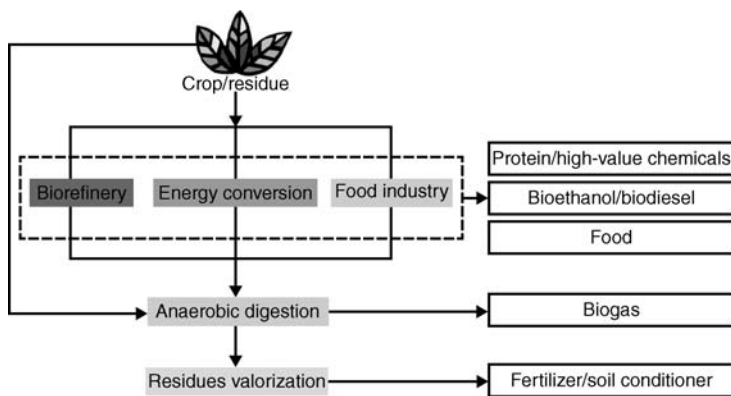
Conditions of residue availability, environmental nuisances associated with them, the demands from the climate change agenda and the world

transition towards a biobased economy are triggering new opportunities for AD (Ahiring and Westermann 2004; Holbein and Layzell 2004; Mata-Alvarez *et al.* 2000; van Dam *et al.* 2005; Verstraete *et al.* 2004). AD is seen to increase its contribution to the biomass chain in two possible ways (Fig. 7.1).

Firstly, AD could be used to directly convert crops into methane as it has been recognized that the technology is competitive in efficiencies and costs to processes yielding other biomass energy forms including heat, synthesis gases and ethanol (Chynoweth *et al.* 2001). AD has also been recognized to be less demanding in resources such as water, nutrients and fossil energy as compared with the more popular biofuel options like biodiesel or bioethanol. In a research studying possible self-sufficiency at farm level in Sweden, the use of biogas was favored over the other two options in terms of its low relative need for arable land, concomitantly resulting in smaller emissions from soil to air and water (Fredriksson *et al.* 2006).

Secondly, new residues (i.e. raw materials for AD) will be generated by other bioprocesses in the form of either diluted waste streams with important organic load or complex solid or semi-solid materials. Here, the flexibility and simplicity of the AD process can add to the economic and environmental sustainability of the entire chain by decreasing waste via the production of additional energy carriers in the form of methane. In addition, AD contributes to closing nutrient and carbon cycles at farm level by means of the reuse of the residual digestate as soil conditioner and the potential recycling of plant nutrients as NH_4^+ and PO_4^{3-} in the digestate liquid or bound to the stabilized fibers in the digestate solids.

In the following sections, a framework for understanding the role of AD within biomass chains is provided. Following that, examples are given



7.1 Possible biogas cascade configurations having anaerobic digestion as a key element.

related to the added value of AD to biofuel chains in Colombia. Finally, generalized conclusions are given and future trends outlined.

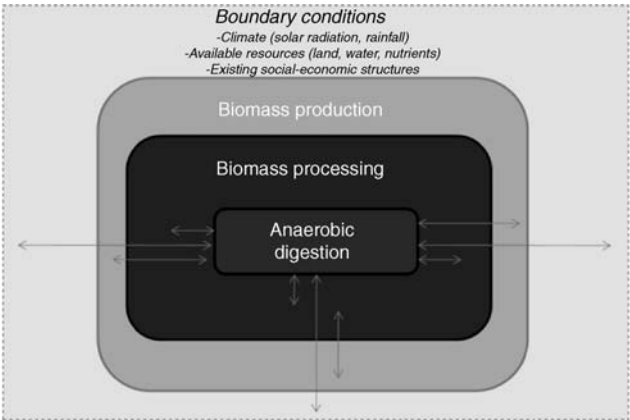
7.3 A framework for approaching the role of anaerobic digestion within biomass chains

Resource cascading – defined as the sequential exploitation of the full potential of a resource on its path towards equilibrium – is a strategy to improve efficiency of materials use (Fraanje 1997; Sirkin and Ten Houten 1994). AD is a technology that can play an important role in increasing the sustainability of biomass cascades by transforming different organic flows into useful products, contributing to the closing of material cycles. Whereas, as noted earlier, the flexibility of the technology can be regarded as its main positive attribute, it is also its main challenge when its contribution towards sustainability is to be assessed, given that biogas systems can take many forms and the differences among possible systems make them complex to study (Borjesson and Berglund 2006, 2007).

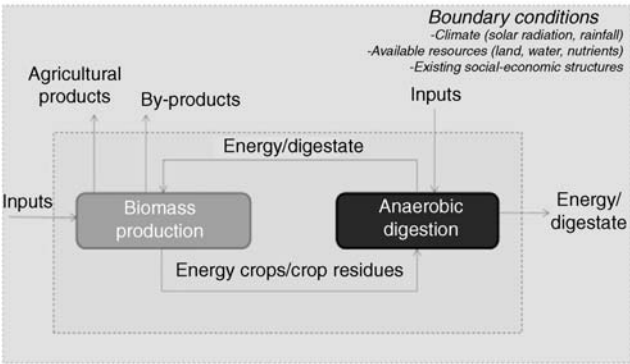
7.3.1 Typology of anaerobic digestion biomass cascades

Biomass systems can have many forms, the biomass follows different routes during its production and utilization time, and the feasibility of a multifunctional biomass system is defined by the main application of biomass (Dornburg 2004).

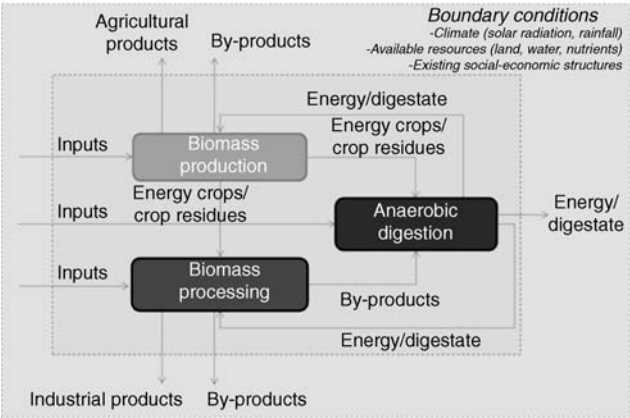
The role of AD can be approached either from a multifunctional perspective, a protagonist perspective or a contributive perspective. In the multifunctional perspective, the role of AD is that of being part of a biomass system comprising many chains and envisaged towards the maximization of its environmental, social and economic outcomes transforming and reusing most by-products following a circular metabolism approach. In the protagonist case, restrictions are not imposed by existing transformative production processes but, in this case, AD is the main process in the chain, like in the case of energy crop cultivation for energy production. In the contributive perspective, AD is incorporated within existing cascades, its added value being defined as a function of the complementary features it can establish with existing processes. These processes will influence both the quantity and quality of the by-products and the possibilities for reuse of the energy and digestate after the AD process. In this sense, the configuration of the other applications producing and transforming the original biomass imposes restrictions that limit the sustainability outcome of the entire system and the specific contribution of AD to the chain (Fig. 7.2).



(a)



(b)



(c)

7.2 Multifunctional (a), protagonist (b) and contributive (c) roles of AD in biomass chains.

7.3.2 Resource efficiency implications of different cascade configurations

Sirkin and Ten Houten (1994) proposed the concept of a ‘cascade chain’, expanding the definition of resource cascading into an operational framework for determining the efficiency and appropriateness of a given resource exploitation within a given context. Their model uses four dimensions for defining or describing a cascade: resource quality, utilization time, consumption rate and salvageability.

Resource quality refers to the extent to which a given resource is fitted to the task being performed. Utilization time refers to the time span over which the resource is used in the cascade. Consumption rate refers to the rate of resource flow and is a fundamental dimension in relation to sustainability as it relates to resource availability for coming generations. Finally, salvageability refers to the degree to which the resource quality of a material can be recirculated to the same chain or alternative cascade chains. The four dimensions defined in the cascade chain model are used to describe the differences in the role of AD from the three defined perspectives in Table 7.1.

Table 7.1 Description of AD cascades based on the four-dimensions proposed by cascade chain theory

Perspective Dimension	Multifunctional	Protagonist	Contribution
Resource quality	Best fitted following maximization of environmental sustainability criteria	Best fitted for AD following maximization of the energy output	Available from the agricultural and industrial processes already in place
Utilization time	Maximized by appropriate use of different fractions of biomass	Defined by the AD process	Prolonged by the introduction of AD for the treatment of by-products
Consumption rate	Adjusted to fit renewability of the resources employed	Adjusted to fit the energy demand	Fixed according to the main use of the biomass
Salvageability	Optimal, as AD potential for closing cycles is fully exploited	Allowed by the incorporation of digestate in the field	Defined by the other industrial processes involved

7.3.3 Quantifying the energy added value of anaerobic digestion within a biomass chain

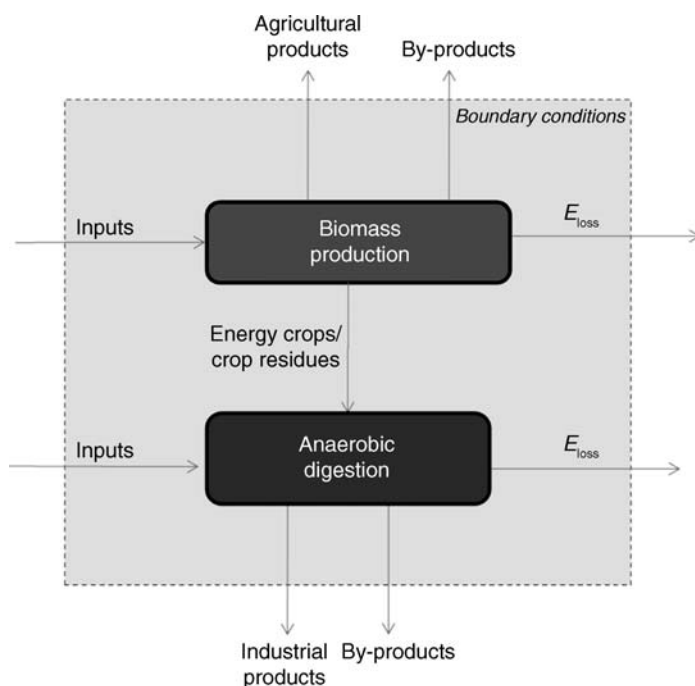
Quantifying benefits of AD plants should include issues such as the substitution of energy, the avoidance of costs related to fertilizer use, hygiene, odor reduction and protection of the environment. Energy is an interesting attribute with which to analyze the role of AD within biomass chains not only because methane as an energy carrier can be regarded as the most significant and visible outcome of an AD unit, but also because it allows the translation of other flows related to the benefits of AD (i.e. different types of nutrients and water) into equivalent units to produce single unit outcomes. In addition, and in view of concerns related to the amount of land being used for bioenergy production and other competing claims, energy savings can be easily translated to equivalent land units, allowing one to draw conclusions at a higher level of abstraction. Similarly, using energy as a parameter allows for comparison with other biofuel production options. The proposed framework for analyzing the role of AD within a cascade departs from the definition of a reference system followed by that of the system with AD embedded. The contributive perspective introduced previously is hereby used to exemplify the proposed approach, recognizing that similar approaches are valid for the other two perspectives, i.e. multifunctional and antagonistic perspectives.

Figure 7.3 shows the situation in a system before AD is introduced. As can be seen, the major flows are inputs to biomass and industrial processes and outputs in the form of products and by-products. Equation 7.1 expresses the situation of a system without AD as the difference between energy outputs, in products and by-products, and energy inputs.

$$E_{\text{bal}} \left[\frac{\text{GJ}}{\text{yr}} \right] = (E_{\text{agriprod}} + E_{\text{induprod}} + E_{\text{by-prod biom prod}} + E_{\text{by-prod ind prod}}) - (E_{\text{input biom}} + E_{\text{input ind}}) - E_{\text{loss}} \quad [7.1]$$

where E_{agriprod} refers to the energy content of agricultural products, E_{induprod} refers to industrial products coming from biomass and $E_{\text{by-prod biom prod}}$ and $E_{\text{by-prod ind prod}}$ refer to the energy content of the by-products or residues coming from the agricultural and the industrial activities, respectively. Further, $E_{\text{input biom}}$ and $E_{\text{input ind}}$ refer to the energy input in both the agricultural and industrial transformation activities, where both direct and indirect energy inputs should be considered. Finally, the term E_{loss} accounts for biomass-linked energy losses.

Once AD has been introduced into a system, the flows in the system change as shown in Fig. 7.4. Products and by-products from the agricultural and industrial systems can be directed to the AD process, which in turn will



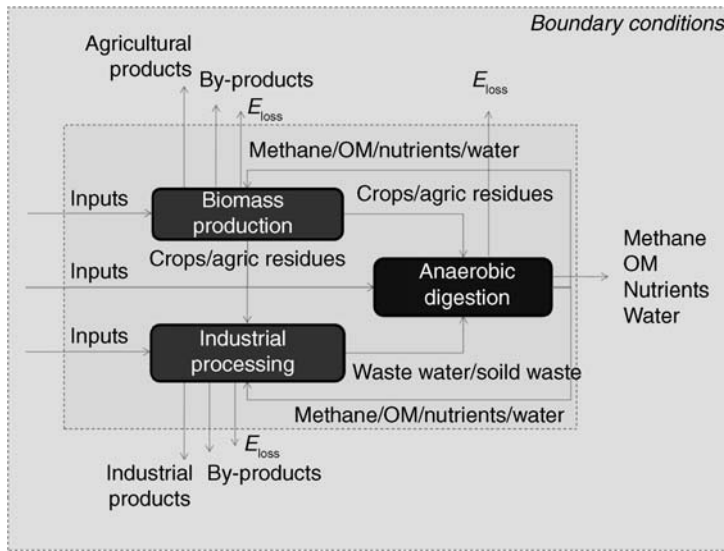
7.3 Biomass chain configuration before introduction of the anaerobic digestion step.

transform them into a useful energy carrier and digestate, i.e. stabilised organic matter, water and nutrients, coming back into the same chain or leaving the system into other systems. The new energy balance can then be expressed by

$$\begin{aligned}
 E_{\text{bal}} \left[\frac{\text{GJ}}{\text{yr}} \right] = & (E_{\text{agriprod}} + E_{\text{induprod}} + E_{\text{by-prod biom prod}} + E_{\text{by-prod ind prod}}) \\
 & - (E_{\text{input biom}} + E_{\text{input ind}}) + (E_{\text{ext output AD}} + E_{\text{int output AD}}) \\
 & - E_{\text{loss}}
 \end{aligned} \quad [7.2]$$

where $E_{\text{ext output AD}}$ corresponds to the energy equivalence of products produced by the AD unit(s) and being exported from the system, whereas $E_{\text{int output AD}}$ refers to the energy equivalence of products from AD used internally for the agricultural production or the industrial transformation units. $E_{\text{input AD}}$ refers to the energy input required for the AD unit operation such as electricity used for pumping, mixing, pre-treating or post-treating by-products. All other terms are as explained in equation 7.1.

The actual contribution of AD to the chain it is embedded in expressed in energy terms can then be calculated as the difference between the energy



7.4 Biomass chain configuration after introduction of the anaerobic digestion step.

inputs required in the second system, that is $E_{\text{input biom2}} + E_{\text{input ind2}} + E_{\text{input AD}}$, as compared with the first case, $E_{\text{input biom1}} + E_{\text{input ind1}}$ and the difference in other energy losses, $E_{\text{loss1}} - E_{\text{loss2}}$ provided no changes other than the introduction of the AD unit in the system exist:

$$AD_{\text{chain contribution}} = (E_{\text{input biom1}} + E_{\text{input ind1}}) - (E_{\text{input biom2}} + E_{\text{input ind2}} + E_{\text{input AD}}) + (E_{\text{loss1}} - E_{\text{loss2}}) \quad [7.3]$$

It is clear that if expanding beyond the system borders (i.e. getting into the multifunctional perspective), the contribution of AD can be much higher than that specific to the chain to which it belongs. This is because AD external outputs are also replacing energy, water, fertilizers and soil amendments in other systems. In addition, and also looking beyond system borders, it is possible that the by-products being used by the AD unit already had a use in other chains in the first case, meaning that when using those substrates as input for AD, energy would be needed to be spent replacing them. Therefore, the overall contribution of AD should also account, for example, for the energy used to produce animal feed which before was coming from the by-products now being transformed by AD. Conversely, in the case where by-products are polluting the environment, a new term should be introduced in the equation that accounts for the energy that would be needed to clean the environment from such polluting load.

Following this reasoning, the overall contribution of AD to different chains can be expressed as

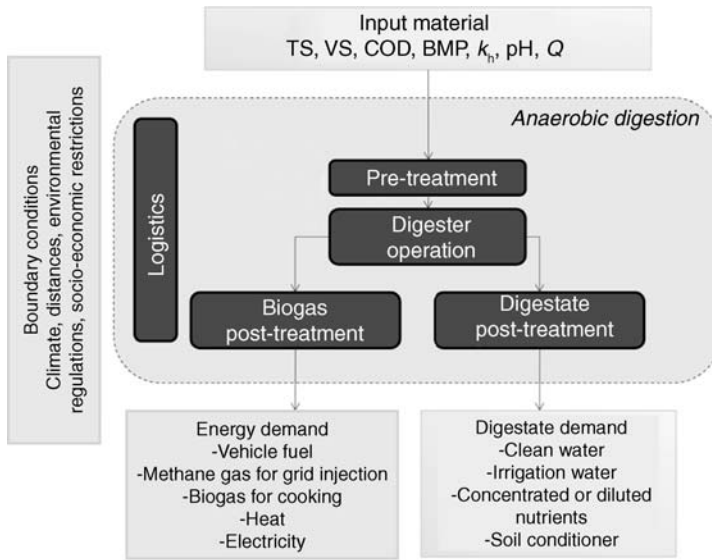
$$\begin{aligned} \text{AD}_{\text{overall contribution}} = & (E_{\text{int output AD}} + E_{\text{ext output AD}} - E_{\text{input AD}}) \\ & + \sum (\Delta E_{\text{input biom}_i} + \Delta E_{\text{input ind}_i} + \Delta E_{\text{loss}_i}) + E_{\text{env}} \end{aligned} \quad [7.4]$$

In equation 7.4, $\Delta E_{\text{input biom}_i}$, $\Delta E_{\text{input ind}_i}$, and ΔE_{loss_i} represent the change in direct and indirect energy requirements in each of the chains (i) where AD products are replacing other inputs or where by-products were previously being used; E_{env} represents the energy that AD is saving in terms of cleaning polluting loads that are now receiving an added value. Basic to the calculations is the energy characterization of the AD unit itself. In fact, despite the simplicity of the AD process itself, the configuration of a full-scale installation usually requires several units, such as storage, pre-treatment, gas and digestate post-treatment, and the overall energy balance of an AD facility is determined by its specific configuration.

The energy balance of an AD facility, $E_{\text{balanceAD}}$, can be defined as the difference between the energy outputs and the energy inputs of the system, both direct and indirect. The direct energy output of an AD facility corresponds to the gross energy produced in terms of methane, E_{methane} , whereas the indirect energy outputs correspond mainly to the energy embedded in the nutrients, E_{nutr} , the indirect energy represented by the water content in the digestate which when given a use is in fact replacing fresh water, E_{water} , and the energy content in the organic matter still present in the solid digestate, which could be recovered for example as a soil conditioner or by means of incineration, E_{OM} . As an indication, 90% dry digested sewage sludge has an energy value of about 10–14 MJ/kg dry matter, i.e. comparable to lignite. Direct energy is used in logistics, E_{log} , pre-treatments, E_{pret} , digester operation, $E_{\text{dig.op}}$, biogas post-treatment, $E_{\text{biog.post}}$, and digestate post-treatment, $E_{\text{dig.post}}$, whereas indirect energy inputs are mainly found in the energy used for inputs different from the energy needed in the process, such as the energy embedded in chemical additives, E_{add} , and that used for the building and maintenance the different operational units, E_{inf} (equation 7.5).

$$\begin{aligned} E_{\text{balanceAD}} \left[\frac{\text{MJ}}{\text{yr}} \right] = & (E_{\text{methane}} + E_{\text{nutr}} + E_{\text{water}} + E_{\text{OM}}) - (E_{\text{log}} + E_{\text{pret}} \\ & + E_{\text{dig.op}} + E_{\text{biog.post}} + E_{\text{dig.post}} + E_{\text{add}} + E_{\text{inf}}) \end{aligned} \quad [7.5]$$

Depending on how the outputs provided by AD are effectively brought back to supply the demands of the chain for energy, water and nutrients, equation



TS, total solids; VS, volatile solids; COD, chemical oxygen demand; BMP, biochemical methane potential; k_h , hydrolysis rate; Q, flow

7.5 External conditions influencing the design of an AD facility.

7.5 can effectively result in net gains in useful energy carriers (e.g. methane), to the specific biomass chain under study.

Given that boundary conditions influence the specific technological configuration of the AD unit as well as the potential to reuse the AD products, the overall contribution of AD within a cascade will result from fine tuning of the AD process to the specific demands coming from the context (Fig. 7.5). Boundary conditions of relevance are climate, transport distances of source biomass, environmental regulations and socio-economic restrictions. Main input material characteristics of relevance are the total solids (TS) and their organic component as defined by the volatile solids (VS) and/or chemical oxygen demand (COD), biodegradability properties in extent and rate as given by the biochemical methane potential (BMP) and hydrolysis rate (k_h), respectively, pH and nutrient content. Obviously, the available amount per unit time or flow, Q , largely determines the specific design. On the other hand, the products of the AD process need to be adapted to the receptive environment according to the demands for energy and digestate.

Energy can be demanded in the form of raw biogas (e.g. for cooking purposes) or in the form of upgraded methane gas for vehicle use or gas grid injection. Furthermore, energy in methane can also be delivered in the form of heat and/or electricity. Finally, decisions regarding digestate post-treatment need to be adapted to the possibilities in the surrounding context for closing material cycles in terms of carbon, nutrients and water.

A more detailed description of energy balances of AD facilities is given in Chapter 9 of this book.

7.4 Contribution of anaerobic digestion to the energy balance of biofuel chains

In recent years, legal restrictions on bioenergy production of liquid fuels have been witnessed in different regions of the world. These have taken the form of fixed targets for the contribution of biofuels to overall automotive energy consumption or compulsory blending regulations of gasoline and diesel with fixed proportions of bioethanol and biodiesel respectively.

Although bioethanol and biodiesel are attractive energy carriers due to their high energy density and liquid character, their perceived environmental and social-economic advantages are being questioned. The main criticisms are directed towards their limited energy gains, the need for fossil fuels or part of energy revenues for their production and the land required for biomass cultivation, which generates undesirable competition with food and other uses of land.

Anaerobic digestion can positively impact the energy balance of both chains via its direct contribution in terms of energy in the form of methane or in its indirect contribution via the replacement of fertilizers, water and extra energy coming from the digestate. Concerns regarding AD technology focus on the fact that the fuel produced is a low energy density gas and not a liquid like biodiesel or bioethanol, implying that higher storage volumes are required. Another constraint is possible emissions of GHG gases if technological units are not managed adequately (Baldassano and Soriano 2000). However, as recently shown by Tilche and Galatola (2008), biogas may make a considerable contribution to GHG emissions reductions, particularly if used as a biofuel. The potential contribution of AD to GHG reduction as computed for 27 EU countries on the basis of their 2005 Kyoto declarations is of the order of magnitude of $3.9 \times 10^9 \text{ m}^3 \text{ CH}_4 \text{ yr}^{-1}$. The sum of bio-methane from landfills and from sewage sludge corresponds to about 380 PJ yr^{-1} . If also considering energy crops, biogas has the potential of covering almost 50% of the 10% biofuel target of all automotive transport fuels for 2020, without implying a change in land use (Tilche and Galatola 2008).

The following examples highlight the role of AD for specific biomass chains in the case of bioethanol production from sugarcane and cassava and biodiesel production from oil palm using the methodology proposed earlier. The cases are examined using Colombian boundary conditions and compare the added value of AD to specific biomass chains for:

- case A, when AD is not present
- case B, when industrial by-products are processed in the digester

- case C, when agricultural by-products are also digested
- case D, when the full plant is digested; here, full plant means above-ground biomass in the case of sugarcane, harvested above-ground biomass minus trunk for oilpalm and total biomass for cassava.

Table 7.2 presents the chains analyzed. The main assumptions for the calculations performed are presented in Table 7.3 and Fig. 7.6 summarizes the results of the assessment on the value of AD for recovering the energy contained in by-products of the biofuel industries. It is important to note that the performed calculations follow equation 7.3 – that is, the added value of AD within a contributive perspective.

As can be seen in Fig. 7.6, great differences are found among the chains studied. When AD is not part of the chain, the contribution of by-products to the energy flows within the chains appears crucial, constituting 41–68% of the sum of all energy flows. In fact, energy in by-products including field residues constitutes 51–71% of the total energy content in the crop. Industrial by-products constitute a lower share of the crop energy as compared with residues from crop production, except in the case of oil palm. The proportion of the energy content present in the aerial biomass as compared with the total energy fixated by the plant is 26%, 7% and 34% for cassava, oil palm and sugarcane respectively. In the case of oil palm, the energy content of the trunks, which are replaced every 25 years, has not been considered. Due to the energy importance of by-products, when they are added value (as in cascades B and C), much higher net energy outputs are produced. The energy content in aerial biomass appears especially relevant when comparing cascades B and C. As can be observed, the net energy output of sugarcane and oil palm become positive only when this flow is included.

Table 7.2 Biomass chains analyzed for the contribution of anaerobic digestion

General description	Flows digested		
	Sugarcane	Cassava	Oil palm
A Biofuel	None	None	None
B Biofuel + AD industrial by-products	Vinasse + bagasse	Vinasse + bagasse	POME + fruit residue + glycerine ^a
C Biofuel + AD industrial by-products and biomass by-products	Vinasse + bagasse + trash	Vinasse + bagasse + leaves and stalks	POME + fruit residue + glycerine + leaves
D Methane from full plant	Full plant	Full plant	Full plant

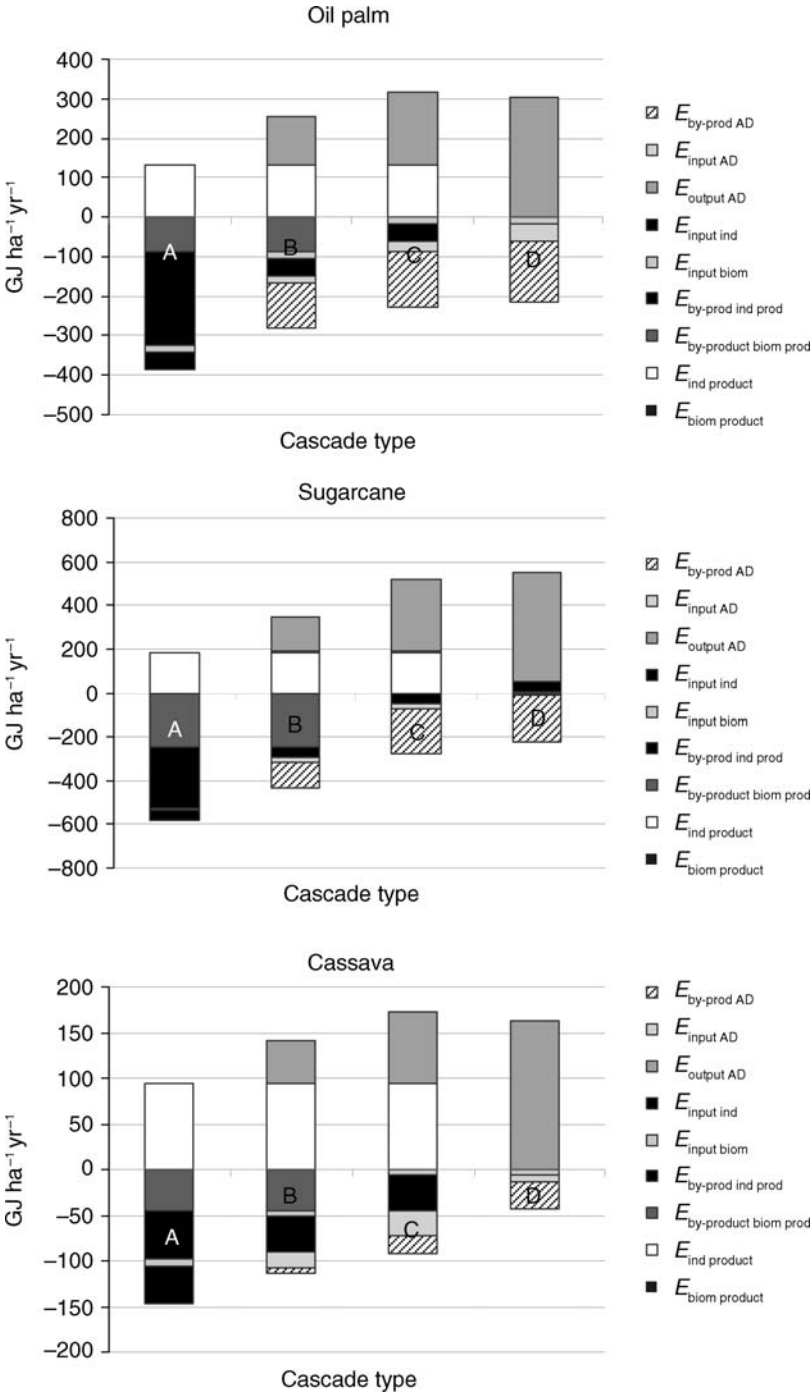
^a POME = palm oil mill effluent.

Table 7.3 Main assumptions employed for the presented energy calculations

	Unit	Bioethanol from sugarcane	Bioethanol from panelacane	Bioethanol from cassava	Biodiesel from oil palm
Energy use for biomass production	GJ ha ⁻¹ yr ⁻¹	9.5	5.5	9.2	16.0
Farming	GJ ha ⁻¹ yr ⁻¹	3	1.7	3	2.2
Fertilizer	GJ ha ⁻¹ yr ⁻¹	4.6	2.7	4.1	13.1
Other inputs ^a	GJ ha ⁻¹ yr ⁻¹	1.9	1.1	2.4	0.7
Energy use for industrial processing	GJ ton biofuel ⁻¹	6.9	6.9	11.1	13.9
Electricity	GJ ton biofuel ⁻¹	1.5	1.5	1.8	0.4
Thermal	GJ ton biofuel ⁻¹	5.2	5.2	9.3	9.3
Other inputs ^b	GJ ton biofuel ⁻¹	0.25	0.25	0.25	4.2
Biofuel productivity	GJ ha ⁻¹ yr ⁻¹	189.1	109.2	93.8	157.9
By-product output					
Green biomass ^d	ton ton ⁻¹ agric product	0.33 (70%) ^c	0.33 (70%)	4.3 (70%)	0.54 (70%)
Vinasse/ POME ^e	ton ton biofuel ⁻¹	19.1 (80%)	19.1 (80%)	17.5 (90%)	2.5 (90%)
Bagasse/Fb + EFB + PKC ^f	ton ton biofuel ⁻¹	5.1 (50%)	5.1 (50%)	3.1 (50%)	3.3 (50%)
Glycerine	ton ton biofuel ⁻¹	—	—	—	0.10 (90%)

^a Considers only pesticides. ^b Energy in additives. ^c In parenthesis assumed anaerobic digestibility. ^d Green biomass corresponds to trash in sugarcane, leaves and stalks in cassava and leaves in oil palm. ^e POME = palm oil mill effluent. ^f EFB = empty fruit bunches; PKC = palm kernel cake.
Source: van Haandel (2005) and Brehmer (2008).

7.6 Distribution of energy flows among energy inputs, products and by-products of alternative cascades based on Colombian biofuel commodities with and without anaerobic recovery of the by-products (cascade types according to Table 7.2). $E_{\text{by-prod AD}}$, energy from the residues remaining in the digestate; $E_{\text{input AD}}$, energy input AD unit; $E_{\text{output AD}}$, energy output AD unit; $E_{\text{input ind}}$, energy input for industrial production; $E_{\text{input biom}}$, energy input for biomass production; $E_{\text{by-prod ind prod}}$, energy in industrial product exported from the system; $E_{\text{by-product biom prod}}$, energy in biomass by-products exported from the system; $E_{\text{ind product}}$, energy in industrial product exported from the system; $E_{\text{biom product}}$, energy in biomass products exported from the system.



Similar energy outcomes as cascade C are produced when the total plant is assumed to be digested, as in cascade D. In this case energy output fluctuates between 90 and 210 GJ ha⁻¹ yr⁻¹. Cassava and oil palm deliver similar results whereas sugarcane offers the highest energy outcome. Due to the limited digestibility assumed for aerial biomass and lignocellulosic residues like bagasse, the energy content left in by-products from AD is still significant. If this energy is to be harvested via combustion, for example, as proposed for sugarcane by van Haandel (2005) or performed nowadays for fresh fruit bunches in Malaysia, the net energy output of cascade B in the case of oil palm and sugarcane becomes positive whereas cascades C and D can almost double their energy output.

The energy balances of the cascades were calculated using equation 7.3. The energy balances for cascades A not benefiting from AD are 72, 128, 45 GJ ha⁻¹ yr⁻¹ for oil palm, sugarcane and cassava, respectively. Extra energy outputs for the different crops fluctuate between 44 and 144 GJ ha⁻¹ yr⁻¹ when only industrial by-products are recovered (i.e. cascade B), whereas when all by-products are valorized using AD, benefits can increase to 71–290 GJ ha⁻¹ yr⁻¹. When the full digestion of the crop is considered, 89–296 GJ ha⁻¹ yr⁻¹ extra net energy outputs result as compared with current biofuel systems being promoted. Such energy still has to be upgraded for final use; in the case of grid injection, this would mean about 15% of the energy content of the biogas produced. If the extra energy recovered from the biomass is expressed as land savings, a minimum saving of one hectare per hectare of land invested could be the case in the least ambitious scenario, which is when only industrial by-products are valorized via AD. In other words, half of the land demanded would be needed to provide the same energy output. Savings from the other systems are even greater when AD is used to valorize the whole crop for energy purposes. In this case, about two times more energy is produced as compared to bioethanol or biodiesel systems, meaning that only 30–35% of the area used to produce the biofuels would be needed to deliver the same energy output.

The added value of AD to biomass chains is also important in terms of nutrient recovery. In the case of cassava, 25–30% total nitrogen, 45–55% total phosphorus and 55–60% total potassium is removed in the root harvest (Howeler 2001) and is therefore expected to be found in the by-products of bioethanol processing, i.e. vinasse, bagasse and fresh fruit bunches/peels. The case of sugarcane portrays a different scenario. In this case, only a minor portion of the nitrogen remains in the aerial biomass, i.e. 10% of the fertilizer applied, the rest being found in the vinasse and bagasse with the majority (80%) in the bagasse. In contrast, phosphorus is mainly found in the vinasse, which can supply 60% of the fertilizer demand whereas bagasse contains only 8% of the phosphorus (Kee Kwong *et al.* 1987; van Haandel 2005). AD seems to be advantageous over other technological

alternatives like combustion, composting or animal feed production to recover this value. If aerial biomass is exported from the system for animal feed production, for example, these nutrients need to be compensated for by the use of additional artificial fertilizer, which implies extra costs that need to be covered by extra income from animal feed sales. If residues are composted, only a fraction of the nitrogen is recovered in the final product (35%). Similarly, if by-products are left in the field to decompose, nutrients are only partially incorporated in the soil for the next cropping season. When combustion is performed, nitrogen is lost but phosphorus and potassium can be partially recovered in the ashes depending on the temperature of the operation used. The advantage of AD to recover nutrients from industrial effluents is especially evident in the case of sugarcane, whereas in the case of oil palm and cassava, the flows from the digestion of aerial biomass are especially important.

The recovery of water via AD represents not only an advantage but a necessity, given the organic load in effluents from biofuel production and the water consumption of crops and industrial processes. Digestion of the whole crop represents very important water savings since digestion can be performed at high solids content, in contrast to the ethanol and biodiesel industries which require large amounts of water. For the studied systems, advantages in terms of water savings from current biofuel producing systems to full AD biomass conversion fluctuate between 1292 and 8789 kton yr⁻¹ for oil palm and sugarcane respectively, i.e. cascade D as compared with cascade C. These values could be expressed in energy terms if considering the energy used in producing fresh water for the purposes of irrigation in the studied systems and added to the overall energy balance. This extra step was not performed in this specific exercise.

From the presented analysis it is clear that AD of by-products from the Colombian biofuel industry can provide substantial land savings as well as significant advantages in terms of water and nutrient recovery. It has also been shown that AD of the full crop can provide similar net energy output as systems producing biofuels and digesting residues, although the quality of the different outputs is different in terms of energy density. Some of the current biofuel systems seem inefficient from the perspective of energy use if considering by-products are exported from the system. However, the ultimate desirability of implementing AD systems to add value to by-products depends on the alternative uses they are actually receiving and the market trends. Since, in Colombia, the infrastructure for delivering natural gas exists for both vehicular and the domestic/industrial market, the feasibility of promoting biogas as an energy alternative will depend on its economic competitiveness with other energy carriers within those markets. Furthermore, the incentives given for the extra benefits provided by the technology (i.e. nutrient provision and water use reductions) can be of

crucial importance when their mass fluxes are adequately considered. The feasibility of AD technology will also depend upon environmental legislation providing adequate valuation of the avoidance of negative externalities from by-products of the biofuel industry such as water pollution and GHG emissions. The latter, obviously, also concerns the appropriate application of AD itself.

7.5 Conclusion and future trends

The analysis proposed and exemplified in this chapter highlights how the contribution of AD to biomass chains can be quantified using useful/recoverable energy as an indicator. Beyond the presented estimations, when analyzing the use of residues for AD, theoretical studies need to consider reality, including issues such as competition for biomass resources and limitations of reuse related to the toxicity of by-products and health concerns. In the first case, for example, palm kernel cake and oil palm leaves are rich in nutrients and have been proven to be feeds of high quality. The same is valid for leaves of the cassava plant. Other by-products (e.g. oil palm fibers and sugarcane bagasse) can be combusted, providing significant energy savings in industrial processes that tend to be intensive in use of thermal energy. This is already being implemented by many industries. On the other hand, other residues such as sugarcane trash, vinasse and palm fruit bunches remain interesting energy sources as their current management generally causes environmental problems.

Beyond the examples of the AD added value to biofuel chains, many other industrial processes can benefit from AD given its potential to treat organic resources of different quality. Table 7.4 lists some by-products that are already being valorized using AD with the concomitant energy benefits. The values given are just indicative as the nature of the biomass material can change considerably according to the circumstances of its production.

The contribution of AD to biomass chains has already been realized and documented in different parts of the world. For example, van Haandel (2005) showed how, by digesting the vinasse and bagasse resulting from the production of ethanol from sugarcane in Brazil, 31.5 GJ can be produced in addition to the 5000 liters ethanol produced from the original total 65–75 ton wet sugarcane. In this way, AD could generate 23% energy of the whole chain. The added value of AD to a grass biorefinery concept has been demonstrated in Switzerland (Baier and Delavy 2005). In this case AD, adds value to the biomass chain by generating 1.8 GJ ton⁻¹ grass in addition to the 0.4 ton ton⁻¹ fibers, and the 0.12 ton ton⁻¹ proteins originally produced from the initial biomass. Future trends towards a biobased economy will strengthen the use of biomass resources for multiple purposes and issues of efficiency in resource use and correct allocation based on environmental and

Table 7.4 Energy potential of different agro-industrial by-products

Substrate	Methane yield	
	m ³ CH ₄ ton ⁻¹ fresh matter	MJ ton ⁻¹ fresh matter
Crop residues		
Straw	139–145	5000–5300
Tops and leaves sugar beet	36–38	1300–1400
Animal residues		
Pig manure	17–22	620–800
Cow manure	7–14	260–510
Slaughterhouse waste	150	5500
Food residues		
Vegetable waste	150–390	5050–12810
Fruit waste	160–710	5100–23170
Industrial effluents ^a		
Alcohol refining	3.9	140
Beer & malt	1.0	37
Coffee	3.2	114
Dairy products	0.9	34
Fish processing	0.9	32
Meat & poultry	1.4	52
Organic chemicals	1.1	38
Petroleum refineries	0.4	13
Plastics & resins	1.3	47
Pulp & paper (combined)	3.2	114
Starch production	3.5	127
Sugar refining	11.2	406
Vegetables, fruits & juices	1.8	63
Wine & vinegar	0.5	19

^a Industrial output expressed per ton wastewater and calculated following IPCC Guidelines 2006, Volume 5, Chapter 6.

Sources: Berglund and Borjesson (2006), Gunaseelan (2004), IPCC (1996) and Lehtomäki (2006).

economic criteria will mean an ever higher contribution of AD technology to efficient biomass utilization.

The evaluation of the gains in resource efficiency of a cascade by AD should be performed on a case by case basis going beyond theoretical estimations into the contextualization of the system. In this way, sustainable resource use can be seen as the result of the integration of the whole biomass chain instead of that of a single product performance.

The question remains of whether the contribution of AD is significant enough to provide sufficient added value to have bioenergy as an option of interest, fitting with the vision of sustainable development. Trends towards the tripling of energy use and the 50% increase in global population by 2050 with concomitant energy-intensive consumption patterns are expected

to generate different levels of disturbance in different regions of the world as their vulnerability changes regarding available resources and demands. Hence, cautious and specific rather than over optimistic and generalized approaches are preferable.

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Abstract: Plant design comprises choice of technology, determination of dimensions and plant layout. The objective is to achieve an efficient installation that allows optimal use of the available resources. This chapter gives an introduction to the technological options, choice parameters and engineering rules of the digestion unit, gas storage, pipework, pumps and valves. The significant influence of feedstock characteristics on the plant design is highlighted throughout the chapter. Process control technology for managing and tracking operations on the biogas plant is also described.

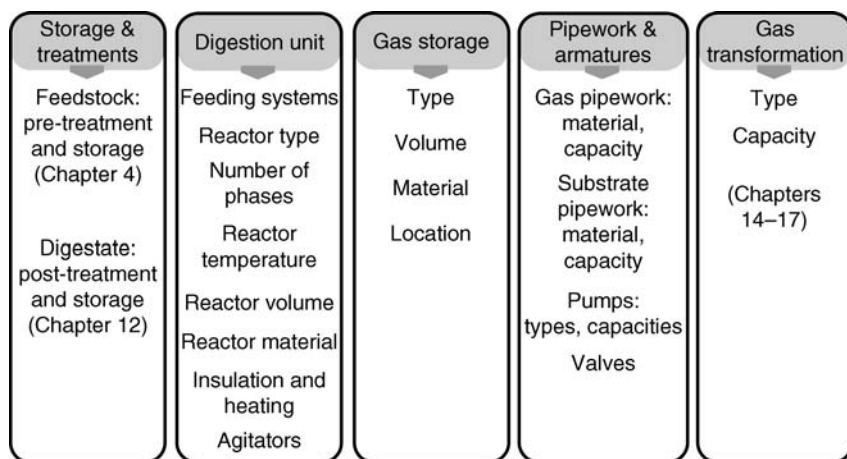
Key words: process technology, design, engineering, feedstock influence.

8.1 Introduction

Plant design is a key step in the development of a biogas project. It comprises choice of technology, determination of dimensions and plant layout. The objective is to achieve an efficient installation, which allows optimal use of the available resources and a progressive impact on the natural and social environment of the plant.

Figure 8.1 shows an overview of the components of plant design, divided into five main groups. Storage, treatments and gas transformation are described elsewhere in this book. This chapter covers the digestion unit, gas storage pipework, pumps and valves. It gives an introduction to the technological options, choice parameters and engineering rules concerning biogas plant design. This chapter also looks at process control technology, used to manage and track the operations of a biogas plant.

The main factors influencing each step of plant design are the composition and the amount of material that will be dealt with. Feedstock characteristics such as dry matter content, acidification potential or pathogenic risk are



8.1 Components of plant design.

fundamental elements. The chemical and biological composition of the substrate or the biogas determines the construction materials needed in order to avoid corrosion. The amount of substrate or gas defines the dimensions or capacity of each plant element. Adapted technology and correct engineering are the basis for a well-functioning biogas plant. It is therefore of vital importance to study the feedstock and the local conditions carefully before taking any design decisions.

8.2 Digestion unit

The digestion unit is the heart of a biogas plant; this is where microbial activity takes place and organic matter is transformed to biogas. The digestion unit is composed of one or several digesters, including feeding, agitation and heating systems. A pre-digestion tank and a post-digester may complete the unit. The technological possibilities are vast, with choices depending mainly on feedstock characteristics such as dry matter content, degradation rate, contaminant and inhibition risks. The main options and designs of different plant components are described in this chapter. Table 8.1 summarises the main processing options for the key parameters of a digestion unit.

8.2.1 Feeding systems

Feeding systems bring the substrates from their storage place into the digester, making the transition from aerobic to anaerobic conditions. They can be simple structures for substrate transport, but there are also elaborate systems that simultaneously allow intermediate storage, mixing, milling,

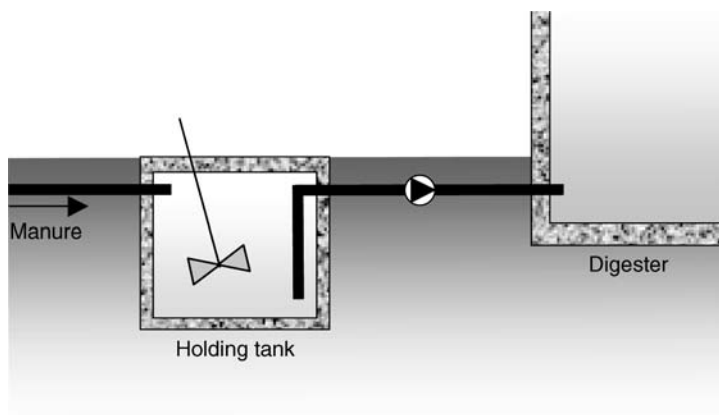
Table 8.1 Processing options

Technology	Key parameter	Options
Feeding system	Digester type and matter content of feedstock	<ul style="list-style-type: none"> • Discontinuous feeding for batch digesters • Continuous or semi-continuous feeding for plug-flow or CSTR digesters • Solid or liquid feeding system depending on dry matter content of the substrate
Reactor type	Dry matter content of feedstock	<ul style="list-style-type: none"> • CSTR for liquid substrates • Plug-flow or batch digester for solid substrates
Reactor temperature	Risk for pathogens	<ul style="list-style-type: none"> • Mesophilic temperature when no risk for pathogens • Thermophilic temperatures when risk for pathogens (organic household waste)
Number of phases	Composition of substrates, acidification risk	<ul style="list-style-type: none"> • One phase systems when no acidification risk • Two-phase system for substrates with a high content of sugar, starch or proteins
Agitation system	Dry matter content of feedstock	<ul style="list-style-type: none"> • Mechanical agitators for high solids concentration in the digester • Mechanical, hydraulic or pneumatic agitation systems for low solids concentration in the digester

weighing and feed-in control with full automation. The degree of technological advancement is mainly dependent on budget.

The feeding system needs to be adapted to both the feedstock and the reactor type. Batch digesters require discontinuous feeding, which is done by wheel loaders, as only solid substrates are employed. Plug-flow and CSTR (continuously stirred tank reactor) digesters are fed continuously or semi-continuously, with different options for liquid and solid feeding. Feedstock pre-treatment, altering the physical characteristics, may change the required feeding system.

Liquid substrates are pumped from a holding tank into the digester (Fig. 8.2). Before pumping, the content must be fully homogenised by mixing. Round and small tanks simplify this process. Solid substrates can be mixed into the holding tank, but the material stream must stay fluid and the pumps must be adapted to higher solid matter contents. More often, solid substrates are fed in separately, through the sidewall or the ceiling of the digester. The advantages of this independent feeding from liquid substrates are the avoidance of clogging risk to the pumps and the possibility of influencing the total solids concentration inside the digester. In the past, chute or flushing systems were used; these are simple and cheap technologies, but involve sudden feeding in high loads, and temperature



8.2 Feeding system: holding tank.

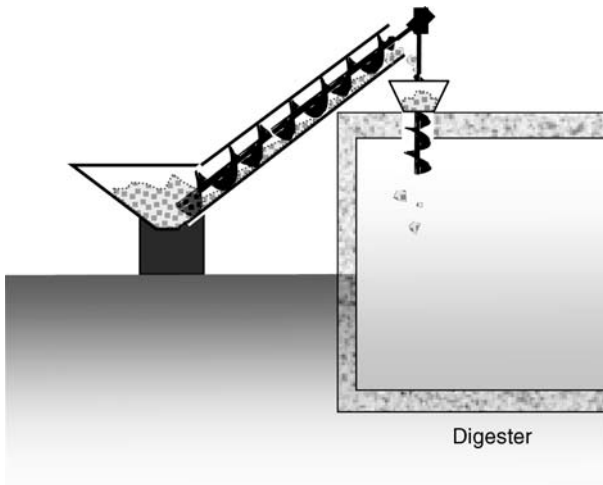
drops and digestion perturbations can be a consequence. Odour emissions are another disadvantage of these systems. Nowadays, screw or piston systems are normally employed, which allow automation and regular feeding in small amounts. They may enclose intermediate storage volumes, allowing automated feeding. Mixers and cutters for homogenising the material or weighing devices are further options to complete the system. The latter are especially useful when precise dosing or tracing of substrates is required.

Screw conveyors bring solid substrates into the digester through the ceiling or the upper part of the side wall, where no hydraulic pressure is present (Fig. 8.3). They are often used in biogas plants, but are prone to abrasion when long fibre substrates or impurities are present in the feedstock.

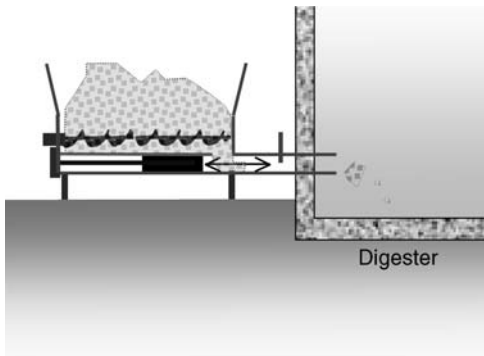
In piston systems, substrates are pressed through a delivery cylinder into the digester (Fig. 8.4). Feeding into the bottom of the digester is possible using a hydraulic actuator, but backflow of digestate must be prevented by valves. A disadvantage of this system is compaction of the substrates by the piston force, which makes it less accessible to the microbes. The formation of sinking layers is also possible.

More than one feeding system can be used to take account of different feedstock types. Feeding management has a significant influence on the fermentation process. Sudden high loads of organic matter or abrupt substrate changes disturb the microbial community and result in a reduction in gas production. Optimal feeding is done regularly in small doses, with a homogenous substrate mix.

In general, the more elaborate and automated a system, the higher its price. At the same time, these systems allow efficient operation with less time



8.3 Feeding system: screw conveyor.



8.4 Feeding system: piston.

investment and optimised feeding, which has a positive influence on gas production. To design a feeding system, two aspects have to be considered: the volume for intermediate substrate storage and the conveyance capacity. Storage capacities within automated feeding systems allow independent feeding over a number of days, which is convenient for operation at weekends and holidays. A storage capacity of 1 to 3 days is usually applied. Conveyance capacity needs to be adapted to the substrate volume and the desired feed-in frequency.

8.2.2 Reactor type

Digestion reactors are characterised by the feeding mode (batch or continuous) and by the mixing type (CSTR or plug-flow); reactor types are described in more detail in Chapter 5. The choice of reactor type is strongly dependent on feedstock characteristics. Batch reactors (usually garage-type systems) are exclusively used for solid feedstocks. As there is no mixing, impurities or fibrous substrates do not disturb the process, which is an advantage of this system. Distribution of micro-organisms happens through water sprinkling from the digester ceiling. If the substrates are too compact, dry zones may appear. Structuring materials such as wood chips and branches help efficient water percolation.

Continuous reactors are either plug-flow or CSTR systems. Plug-flow reactors are used for solid feedstocks. The entering substrates push material through the digester, and this plug-flow effect can be achieved when the dry matter content of the substrate mix is above 20% at the entrance of the digester. CSTRs are used for low dry matter content substrates. Solid substrates can be introduced as long as the dry matter content of the substrate mix in the digester stays below 15% (Görisch and Helm, 2006). Above this level, complete mixing of the reactor contents cannot be guaranteed. In plants with more than one digestion tank, plug-flow digesters and CSTRs can be combined and substrates can go through one or both of them depending on their dry matter content and degradation rate.

8.2.3 Number of phases

Most biogas plants function within a one-phase system, which means that all the steps of microbial degradation take place in the same tank. The advantages of this method are simple processing and lower investment costs. By contrast, a two-phase system separates the hydrolysis stage from the process (in a separate tank); pH, temperature and retention time can be optimised for each phase. This leads to better degradation kinetics and is recommended for substrates with a high content of sugar, starch or proteins. During the hydrolytic phase, these easily degradable substances produce large amounts of acids, which inhibit methane formation in a one-phase system.

8.2.4 Reactor temperature

According to the temperature in the reactor, there is a distinction between psychrophilic (10–25°C), mesophilic (25–45°C) and thermophilic digestion (50–58°C). The temperature in the reactor affects several parameters, each having a significant influence on the digestion process.

- *Degradation rate.* The higher the temperature, the faster the degradation of the organic matter. Thermophilic digesters require shorter retention times and therefore smaller reactor volumes.
- *Hygienisation effect.* The higher the temperature, the better the pathogen inactivation during digestion. In accordance with national legislation, thermophilic digestion can replace feedstock pre-treatment by hygienisation.
- *Process stability.* The higher the temperature, the higher the sensitivity of the process to changes in temperature, pH and feeding rate. Furthermore, high temperatures enhance the transformation of ammonium (NH_4) to ammonia (NH_3), which increase the risk of microbial inhibition.
- *Energy consumption.* The higher the temperature, the higher the energy demand.

Psychrophilic temperatures occur in biogas plants without heating systems, such as family-size biogas plants, mainly in developing countries. Degradation is too slow for reactors with high efficiency requirements. Mesophilic temperatures, which allow satisfactory retention times and moderate energy demand, are the most commonly used. In particular, CSTRs with a high water content should not have excessive energy consumption for heating in order to maintain a reasonable global energy efficiency. Thermophilic temperature ranges are mainly used for substrates with a hygiene risk, typically food wastes. In plants with more than one digestion tank, thermophilic and mesophilic reactors can be combined and substrates can go through one or both of them, depending on their pathogen risk and degradation rate.

8.2.5 Reactor volume

The reactor volume needs to be adapted to the amount of feedstock and the degradation rate of the key substrates. On the one hand, micro-organisms must have sufficient time for the degradation process and, on the other, the concentration of organic matter must not be of a level that leads to over feeding of the microbes and thus process inhibition. To ensure the right balance is achieved, two parameters are used to calculate the digester volume – the organic loading rate (OLR) and the hydraulic retention time (HRT).

The OLR describes the amount of volatile dry matter (VDM) introduced into the digester, expressed in kilogrammes VDM per day and per cubic metre of digester ($\text{kg VDM/m}^3\text{day}$). For CSTR digesters, the OLR is typically between 2 and $3 \text{ kg VDM/m}^3\text{day}$. It can go up to 4 or even $5 \text{ kg VDM/m}^3\text{day}$, but the higher the organic load, the more sensitive the

system becomes and more monitoring is required (Eder and Schulz, 2006). Plug-flow digesters function with a higher OLR, up to 10 kg VDM/m³day. The formula for calculating the organic load is given by equation 8.1. The digester volume includes the volume of the post-digesters.

$$\text{OLR (kg VDM/m}^3\text{day)} = \frac{\text{Substrate input (kg/day)} \times \text{DM (\%)} \times \text{VDM (\% of DM)}}{\text{Digester volume (m}^3\text{)}} \quad [8.1]$$

The HRT describes the theoretical time period that the substrates stay in the digester. It describes the mean retention time that, in reality, deviates from this value, especially in CSTR systems where shortcuts occur. The HRT must be chosen in order to allow adequate substrate degradation without increasing the digester volume too much. Washout of the microbes must absolutely be avoided, therefore the HRT must not be below 10 days (Eder, 2006). The HRT is calculated from

$$\text{HRT (days)} = \frac{\text{Net digester volume (m}^3\text{)}}{\text{Substrate input (m}^3\text{/day)}} \quad [8.2]$$

Both the OLR and the HRT make reference to the effective digester volume, which is the volume actually available to the substrates. To obtain the total digester volume, the headspace above the liquid level (eventual gas storage) needs to be taken into account. Box 8.1 shows a worked example.

8.2.6 Reactor material and protection

Digestion tanks of reinforced concrete and steel are most widely used. Reinforced concrete tanks benefit from the high tensile strength of steel and high compression strength of concrete. Appropriate concrete quality (blast-furnace cement and low lime content) and professional construction are important to prevent corrosion and leaks in the tank wall. Concrete digesters can be built partially or completely in the ground. Steel digesters are built on concrete foundations above ground. Steel plates are welded or bolted together and seams are tightened. For parts in contact with corrosive fluids highest quality stainless steel is recommended (Eder and Schulz, 2006). Glass-coated or galvanised steel is used when there is no risk of corrosion.

Vulnerable parts of the reactor should be protected by coatings or liners in order to avoid corrosion. Substrates, biogas and condensate can contain aggressive substances (e.g. hydrogen sulphide, ammonia, organic acids and even microbes) that disintegrate concrete and plastic. In steel and concrete reactors built from high-quality materials, the zone in contact with the substrate does not normally need protection, but the zone in contact with

Box 8.1 Worked example

A farmer wants to build a biogas plant. Amounts and characteristics of the two available substrate types are

- slurry 9000 t/year, 8% DM, 85% VDM (density: 1 t/m³)
- food waste from restaurants 500 t/year, 16% DM, 82% VDM (density: 0.75 t/m³)

Calculate the effective digester volume, when ORL is fixed at maximum 3 kg VDM/m³ day and HRT at minimum 37 days. Which is the determining parameter, HRT or OLR?

Solution

Total organic matter: 678 t VDM/year

Total substrate volume: 9667 m³/year

Volume calculation in regard to OLR: $V = 1856 \text{ kg VDM/day} / 3 \text{ kg VDM/m}^3 \text{ day} = 619 \text{ m}^3$

Volume calculation in regard to HRT: $V = 26.5 \text{ m}^3/\text{day} * 37 \text{ days} = 980 \text{ m}^3$

HRT is the determining parameter. The effective digester volume must be minimum 980 m³

The organic loading rate is 1.9 kg VDM/m³ day.

gas should be protected by a plastic layer in order to resist small deformations or hairline cracks in the material. It must also be resistant to temperature variations, humidity and to aggressive substances that may be resident within reactors.

Bitumen, emulsion paints (for underwater use), polyurethane, polystyrene or epoxy are used for coatings. They are applied by painting, spraying or by spatula and must form a tight and completely covering layer. The application of a primer can be helpful, especially in the case of rough surfaces. Lining sheets are another protection option. Polyethylene tiles or films can be set up in cast form and sealed with concrete.

8.2.7 Reactor insulation and heating

A constant temperature in the digester is essential for a stable digestion process; digesters are therefore insulated and heated in order to reduce and compensate heat losses. Feedstock may also be heated before entering the digester, which helps to avoid temperature fluctuations.

Reactor insulation can be placed inside or outside the digester wall, the advantage of the latter being full availability of the digester volume. Mineral wools (glass, rock and slag wools) and foamed plastics are the most commonly used and approved materials (Eder and Schulz, 2006), but

organic materials such as sheep wool, cotton, flax, coconut fibre, etc. can be used although they are considerably more expensive. The thickness of the insulation is designed in order to optimise the costs of the insulation in comparison with cost savings due to reduction of heat losses. As a rule of thumb, aimed heat transfer values are $0.3 \text{ W/m}^2\text{K}$ for mesophilic reactors and $0.2 \text{ W/m}^2\text{K}$ or less for thermophilic reactors (Eder and Schulz, 2006). The resulting insulation thickness is 10–18 cm.

For reactor heating, hot water passes through pipes in the digester. Heating pipes used to be cast in the concrete wall and floor, but tension due to temperature differences can cause cracks in the concrete and wear the system. Hence, heating pipes are now commonly placed on the inside of the digester wall.

The required heating power depends mainly on the digester temperature, volume, form and insulation as well as the temperature of the fed substrate and the ambient climate. To estimate the required power, the following three components are calculated and summed.

1. Power for substrate heating (inside or outside the digester)

$$P = RC\Delta T \quad [8.3]$$

where R is the mean feeding rate (g/s), C is the specific heat (specific heat of water = 4.186 J/g K) and, ΔT is the temperature difference between incoming substrate and digester (K).

2. Compensation of heat losses through radiation

$$P = \Delta T' SU \quad [8.4]$$

where $\Delta T'$ is the temperature difference between the outside and inside of the digester (K), S is the digester surface area (m^2) and U is the heat transfer value of the digester wall ($\text{W/m}^2 \text{ K}$).

3. Compensation of heat losses through evaporation

$$P = FESat \quad [8.5]$$

where F is the flow rate of produced biogas (m^3/s), E is the evaporation enthalpy (evaporation enthalpy of water 2.260 kJ/kg) and, Sat is the water saturation of produced biogas (kg/m^3).

Most frequently, 'waste' heat from a combined heat and power (CHP) unit is used as the energy source for digester heating.

Table 8.2 Mechanical agitators

Type	Description	Application field
Submersible propeller agitator	High-speed agitator with two- or three-blade propeller, installed horizontally or inclined. Height of agitator is adjustable. Up to 1500 rpm	CSTR digesters with temperature up to 40°C (Eder and Schulz, 2006). Can be used as secondary agitator (e.g. to destroy layers)
Rod mixer	High-speed agitator installed at the ceiling or sidewall of the digester. The motor stays outside the digester. Up to 1000 rpm	CSTR digesters. In case of large propellers and low rpm, it is also appropriate for higher solid contents
Paddle agitator	Low-speed agitator composed of a central driving shaft with paddles, which turn transversal to the flow direction. No current is produced. Up to 20 rpm	Plug-flow and CSTR digesters. Appropriate for high solids concentration and fibrous substrates

8.2.8 Agitators

Agitation of the digestion material is important for distributing the substrates, micro-organisms and heat; it also helps to drive out gas bubbles and avoid the formation of floating or settling layers. Agitation is done at intervals, with the length and frequency of the intervals being determined for each plant. In the beginning, agitation should be done in long and frequent intervals. Gradually, it can be reduced while observing the performance and eventual layer formation. Models can be used for simulating flow behaviour inside the digester. Computational fluid dynamics (CFD) programs can be used to predict particle movements as a function of digestion substrates and certain plant parameters.

There are three main forms of agitation techniques – mechanic, hydraulic and pneumatic.

- Mechanical agitators frequently used are propellers or paddles that cause mixing by their own rotational movement. They are distinguished by their shape, rotation speed and diameter. While small and fast propellers work for liquid substrates, larger and slower paddles are used as dry matter content increases. The most common types of mechanical agitators are submersible propeller agitators, rod mixers and paddle agitators. Their characteristics and application fields are described in Table 8.2. The disadvantage of mechanical agitators is their sensitivity to abrasion. Serious damage can be caused by unadapted feedstock, such as substrates with high sand content, metallic or glass residues. Repair to the agitators is laborious because accessing the damage

requires removal of the agitation system. In the case of paddles, the digester has to be emptied.

- Hydraulic agitation works by creating a strong hydraulic current that mixes up the material. The substrate is withdrawn from the digester and returned with pressure through a nozzle. A powerful pump is needed, but the same pump can be used for feeding from the holding tank. One advantage of this system is that wearing parts are outside the digester and are therefore accessible. Hydraulic agitation is an efficient solution, but there is a risk of clogging of the system by too dense or fibrous substrates.
- Pneumatic agitation functions by the injection of biogas under pressure at the bottom of the digester. Rising gas bubbles induce vertical movement in the tank, which causes substrate mixing. The gas nozzles have to be distributed evenly to avoid static zones in the reactor. This technique works well for liquid substrates, but it is also applied in vertical plug-flow digesters for solid substrates such as source-separated municipal waste.

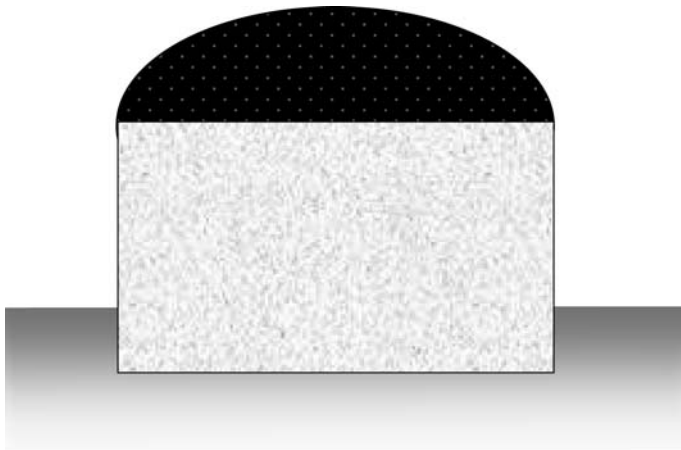
8.3 Gas storage

Fluctuations and peaks in biogas production commonly occur. To dampen the effect of variable gas production and to allow a controlled flux to the transformation unit, biogas is gathered and temporarily stored. Due to this buffer volume, irregular consumption (e.g. by CHP units) can also be counterbalanced. Storage facilities need to be gas tight and resistant to pressure, UV irradiation, temperature variations and harsh weather conditions such as hail. The storage system also needs to be equipped with a sensor to detect over- or under-pressure. Different recommendations for storage capacities can be found in the literature; for example

- Eder and Schulz (2006) indicate a storage capacity for 5–12 hours of gas production in the case of co-generation
- Deublein and Steinhauser suggest (2011) a storage capacity for 12–18 hours of gas production for co-generation
- Görisch and Helm recommend (2006) an average storage capacity for 4 hours of gas production.

Usually, the storage volume is chosen as a function of space availability and budget. Many biogas plants function with 2–3 hours of storage capacity, or even less in the case of biogas upgrading.

One possibility is to store the biogas directly inside the digester. In this case, a flexible membrane is used as both digester roof and storage volume (Fig. 8.5). When the gas production rate is higher than consumption, the membrane extends. To avoid contact between the deflated membrane and

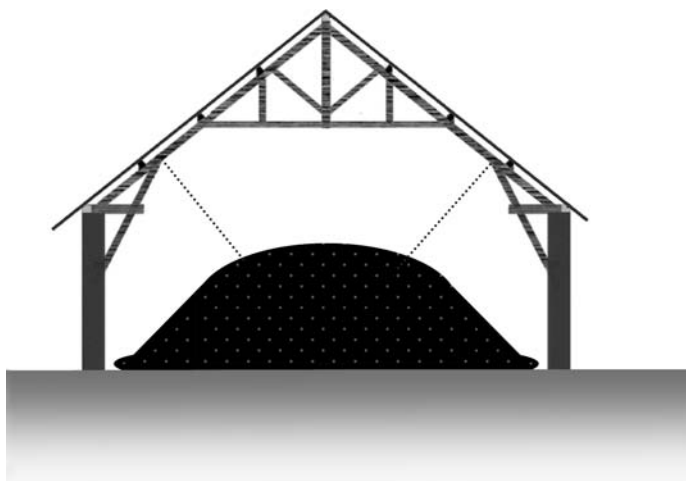


8.5 Internal gas storage.

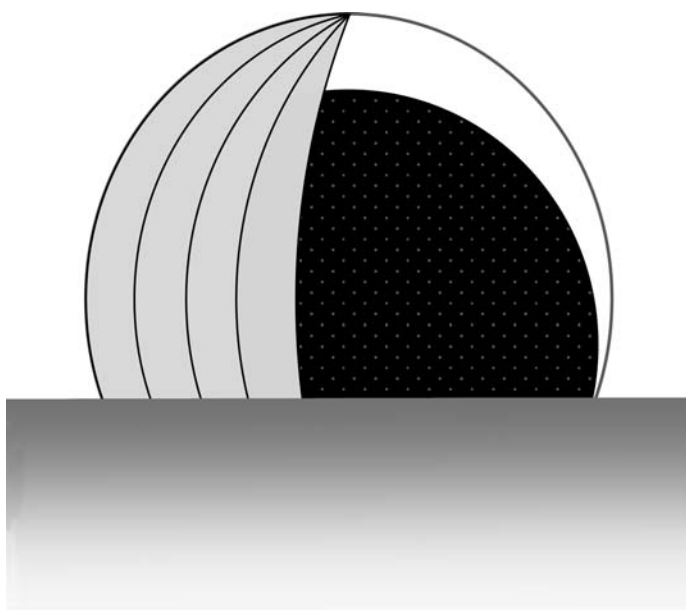
the digesting material, a structure is installed horizontally at the top of the digester, supported by a central pillar. In the case of simple membranes, EPDM (ethylene propylene dienemonomer) rubber is usually used due to its good UV resistance and elasticity. For double membranes, soft PVC is used. An air blower between the two layers constantly inflates the outer membrane, protecting the inner membrane, which inflates and deflates with gas volume.

Another possibility is external gas storage, meaning that the storage place is separate from the digester. Formerly, floating roof gas holders were used. Gas vessels were placed on tanks filled with water, which provided an elastic gas-tight seal and the vessel could rise or fall depending on the gas volume. Nowadays, flexible structures are preferred for external gas storage. For example, membrane cushions are a convenient and cost-effective solution, existing in many different configurations (Fig. 8.6 and Fig. 8.7). They can be placed on the digester roof or elsewhere, but they should be protected by a double membrane or by a shelter.

The over-pressure in such gas holders is around 0.05 bar. In consequence, the space requirement for the storage is important: 1 Nm^3 of biogas, containing approximately 6 kWh, occupies about 0.95 m^3 . In rare cases, medium (5–20 bar) or high-pressure (200–300 bar) storages are used, which allow significant reductions in volume (1 Nm^3 may be reduced to less than 4 l in a high-pressure storage). However, these types of storage require expensive steel constructions and energy-consuming gas compression and decompression.



8.6 Gas storage: membrane cushion with shelter.



8.7 Gas storage: membrane cushion with double membrane.

8.4 Pipework, pumps and valves

For material transport and flow control, adapted infrastructure is necessary. Pipework, pumps and valves need to resist physical and chemical stress that may be caused by substrates and biogas. Choosing the right type, material

Table 8.3 Choosing pipework

Key parameter	Required pipe characteristics
Transported material and pipe location	Biogas pipes made of stainless steel if the pipe is above ground and polyethylene (PE) if below ground. Pipework for substrates and digestate are generally PVC, PE or steel
Temperature of the material	PVC and PE are fit for temperatures up to 60°C. Above this, steel should be used (e.g. after hygienisation unit)
Pressure in the pipe	Pipes under pressure are usually made out of steel. If plastic material is used, the wall thickness must be increased. The pipe diameter varies between 100 and 150 mm – big enough to prevent obstructions, but small enough to prevent pressure losses and sedimentations. Overflow or return pipes are generally PVC and have larger diameters of 200–300 mm (Eder and Schulz, 2006)

and diameter is essential to avoid major problems during operation such as clogging and abrasion.

8.4.1 Pipework

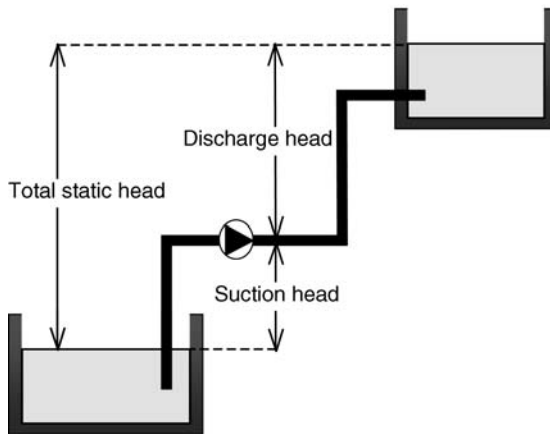
Substrates and gas are transported in pipework. Pipe material and diameter must be chosen with regard to the transported media and its temperature, pipe location and pressure in the pipe. The relationships between these parameters and pipe characteristics are described in Table 8.3. All pipes need to be protected from frost, which can be done with heat insulation and tracing. Necessary devices in pipework are also inspection and cleaning apertures to allow access to the problem area in the case of pipe clogging.

8.4.2 Pumps

When flow by gravity is not possible, pumps convey material from one place to another. A pump needs to be adapted to the conveying material and the total dynamic head (TDH). Dry matter content and the risk of containing impurities must be considered; while some pump types are very sensitive to variations, others are relatively robust.

The total head is the equivalent height that feedstock needs to be pumped, taking account of the suction head and discharge head (Fig. 8.8). To calculate the TDH, head losses, caused by the friction between fluid and pipes due to roughness, direction changes or valves, also have to be considered. The formula is

$$\text{TDH(m)} = \text{Suction head(m)} + \text{discharge head(m)} + \text{friction losses(m)} \quad [8.6]$$



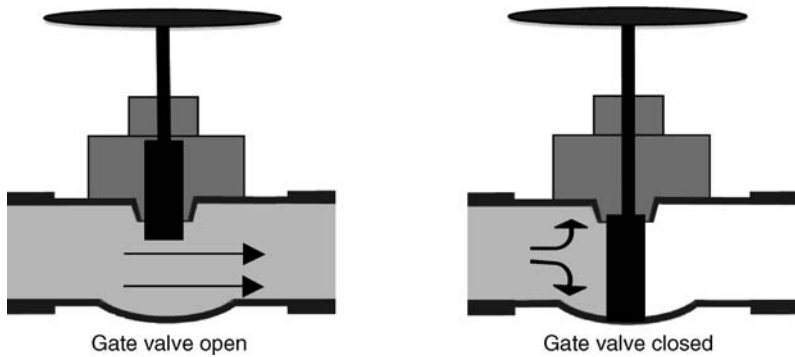
8.8 Total static head.

Two main pump groups can be distinguished among those utilised in biogas plants: centrifugal and displacement pumps. Centrifugal pumps are used for liquid substrates with dry matter content less than 8%, which is typically the case for slurry. These pumps are robust and can generate pressures up to 20 bar, but the conveying capacity is strongly dependent on pressure losses due to the head and friction. In the case of fibrous substrates such as straw, centrifugal pumps can be equipped with cutters for breaking down the fibres and thus preventing clogging. A weak suction head is a disadvantage of this pump type.

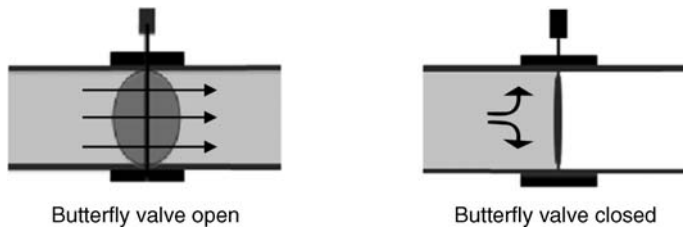
Displacement pumps are used for substrates with a higher dry matter content. They can convey material forwards and backwards, and their conveying capacity is much less dependent on head and friction. Eccentric screw pumps, also called progressive cavity pumps, are one type of these pumps. They function with a metallic rotor in the form of a helix, which turns eccentrically in a stator with a twin helix. Material can be transferred at very low flow rates, although high pressures can be generated. A disadvantage is their sensitivity to impurities, fibres or idle running. Another type of displacement pump is the rotary lobe pump. Material is trapped in the cavity of the lobes and is displaced as they rotate. These pumps are resilient to impurities and fibres and so are frequently used in biogas installations.

8.4.3 Valves

Valves are used for regulating, directing or controlling the flow. Depending on the flow media and the specific requirements, different valve types are employed. The main valve types used in biogas plants are gate valves, butterfly valves and check valves.



8.9 Gate valve.



8.10 Butterfly valve.

Gate valves function by lifting and shutting a gate to let pass or suspend the flow (Fig. 8.9). They close tightly, but lifting and shutting of the gate using a hand wheel is rather slow. In case of fibrous substrates, the gate must be equipped with a cutter to prevent leakage. Butterfly valves are also used to block the flow in a pipe (Fig. 8.10). The closing disc, fixed to a rod, is connected to an actuator on the outside of the valve, which allows the valve to be positioned parallel (valve open) or perpendicular (valve closed) to the flow. This valve type can be closed and opened quickly, but it does not close completely tight. Check valves allow material flow in only one direction. They are used when backflow must be prevented. As impurities can cause leakages, a gate valve must be installed in addition to a check valve.

8.5 Site characteristics and plant layout

The layout of a biogas plant can take various forms. It must be elaborated specifically for each project, depending on site characteristics such as size, form and existing infrastructure. Some basic rules concerning the requirements of a plant site and the integration of a biogas project in a given framework are as follows.

- A site with sufficient space is compulsory, including storage areas, zones

for technical equipment and the plant itself. The plant layout must allow easy access for vehicles to the storage facilities for substrate and digestate. Plant components that require controls must be able to be reached easily. In the case of eventual feedstock increase, the layout should also allow expansions such as additional digesters and storage areas.

- Basic infrastructure should be present on a project site, including close access to roads, water and electricity. Existing facilities on the site (e.g. tanks, storage places, buildings and vehicles) should be integrated as far as possible into the planning in order to keep costs low. Legal limitations may exist and should be checked for conformity.
- The plant site should offer possibilities for energy use or transport. The presence of a natural gas pipeline in proximity gives the option of biogas upgrading to biomethane and injection into the grid. In the case of transformation by co-generation, utilisation of the produced heat should be considered: district heating schemes or nearby industrial processes are frequent purchasers. The transformation unit should be placed near the injection possibility to the electricity, heat or gas grid.
- Transport distances for feedstock and digestate on the site must be kept as short as possible in order to ease operation of the plant.

8.6 Process control technology

Process control technology helps to manage and track plant operations. Parameter registration and plant control can be automated, which simplifies the work of the operator and allows independent running of the plant during weekends and holidays.

Most plants use a programmable logic controller (PLC) for process control. This consists of a central processing unit (CPU) and different modular units, which must be chosen depending on the individual needs for the plant. When programming the processor, the desired degree of automation is chosen. The processor allows converting inputs into reactions of the controlling unit. The inputs can be measurements or time-controlled signals, leading to a specific action on the plant such as closing valves, starting mixing, giving alerts, etc. Visualisation of processes is also part of the control system; individual and connected processes can be displayed. Selected measurements and activities are saved onto a database, which allows long-term monitoring. Further options for control systems are e-mail and sms alarm functions or the possibility of remote controlling where the internet is used for data transfer.

Despite all technological progress, every plant must keep the option of manual control for the case of unexpected events or breakdown within the controlling technology.

8.7 Social and legal aspects

When planning a biogas installation, the social and legal conditions of the plant site must be integrated in the project approach. Public acceptance of a biogas project is important, but usually not an easy achievement. People are very concerned about impacts such as odour, noise and undesired landscape changes and the appearance of bad examples in the media amplifies these fears. During the permission procedures, objections from the population can slow down or even prevent a project. To avoid such difficulties, the population concerned should be informed at an early stage of the project. Willingness to discuss and taking apprehensions seriously help to prevent and reduce problems during the permission procedures, as well as during operation of the plant.

The regulations concerning biogas plants are different from one country to another, and regional regulations must also be considered. Early contact with the municipality and the permission authorities can be helpful. In particular, zone conformity and distances to buildings, forests, rivers, lakes or sources must be respected. Emission regulations or compensating measures are other possible constraints.

8.8 Practical challenges and future trends

Since the growth of the biogas sector in the late 1990s, mainly in Germany, knowledge about biogas plant design and engineering has constantly improved. The technology has developed strongly and new and optimised solutions have been proposed. Today, the technological options are vast and the main challenge is choosing the best option for a specific situation. Problems in biogas plants are primarily due to human failures or negligence, either during design and engineering or during operation. Problems such as pipe clogging, material abrasion, floating layers and sedimentations in the digester frequently happen due to technology that is not adapted to the feedstock or to feedstock that is not adapted to the technology.

In the field of plant design, the challenges mainly concern economic optimisation. Technologies allowing lower investment and operation costs are of great interest in the biogas market. In countries where subsidies and feed-in tariffs are low, projects can be viable only if costs go down. Furthermore, substrates that are at present economically uninteresting for anaerobic digestion could become attractive. Some further trends and developments are as follows.

- *Mixing optimisation.* Mixing of the digester content is a process with high electricity consumption. The challenge is to adapt mixing intervals and intensity in order to minimise energy consumption but still fulfil the

mixing purpose, and models have been developed to predict flow behaviour in the digester (CFD programs). These models have yet to be approved and standardised for different feedstock, digester and agitator types.

- *Small-scale digestion concepts*. Small-scale biogas projects (<100 kW) are often abandoned after the first economic calculations due to investment costs that are too high in comparison to the benefits. Nevertheless, biogas plant constructors are starting to propose low-cost small-scale concepts, aimed particularly at animal slurry processing. The technical and economic efficiency of these systems is yet to be evaluated.
- *Membrane bioreactors (MBRs)*. The objective of MBRs is to improve the efficiency of digestion reactors and reduce reactor volumes. Solid matter is separated from the feedstock, and only the liquid fraction enters the digester. The effluent passes through an ultrafiltration unit, separating water and active biomass, and the latter is returned to the digester. Substrates with low dry matter content, such as slurry or sewage sludge, could become more interesting substrates for biogas production. At present, MBRs are not an approved technology in the field of anaerobic digestion. Research towards their standardisation is ongoing.

8.9 Sources of further information and advice

Information on plant design and engineering is given mainly in German literature, due to the strong development of the biogas sector in German-speaking regions. Books and brochures with further information and illustrations are as follows.

Eder and Schulz (2006) give detailed design and engineering explanations, complete with checklists, examples and exercises (in German).

Deublein and Steinhauser (2011) give wide information on plant components (in English).

Al Seadi *et al.* (2008) offer broad information on plant components (in English).

CLA publication 49 (CLA, 2009) gives details on technology, plant sizing, costs and regulatory framework. The document gives illustrations with case studies and legal information and costs applying specifically to Great Britain (in English).

Görsich and Helm (2006) present technical data and descriptions of frequent damages and rehabilitation possibilities (in German and French).

FNR (2010) gives technical data and explanations on what, when and by whom the different steps of a project are accomplished. Legal information and proceedings apply specifically to Germany (in German).

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Energy flows in biogas plants: analysis and implications for plant design

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Abstract: Biogas plants offer a positive contribution to greenhouse gas mitigation and renewable energy supply; an energy balance is key to the evaluation and optimisation of this contribution. This chapter discusses the energy demand of biogas plants and methods for its evaluation. Suggestions are also put forward for the optimisation of the energy balance, including the reduction of parasitic energy demands and the avoidance of energy losses. It is suggested that biogas technology will be able to fulfil forthcoming demands for increased energy efficiency and sustainability.

Key words: energy balance, heat demand, electricity demand, fuel demand, energy loss reduction.

9.1 Introduction

The desire for economic and ecological efficiency will increasingly lead to the application of a specific biogas technology on a commercial scale. Investors seek to compare and evaluate technological prospects not only on the basis of investment and operational costs and biogas yields, but also on the basis of greenhouse gas emission reduction (carbon credits) and renewable energy supply targets. The energy efficiency of a biogas plant must therefore be evaluated and optimised using an energy balance approach. Unfortunately, in many cases, reliable data for the comparison of different technologies are unavailable. Moreover, most investigations focus only on electricity or heat demand, while fuel demand for transport is generally ignored. Experience has demonstrated that there is a relationship

between electricity, fuel and heat demand; furthermore, these are also dependent on factors such as substrate parameters and climatic variations over the year, meaning that a single static average energy demand will never reflect the true energy demand behaviour of the plant.

This chapter aims to provide an overview of the data required for energy balance analysis, both in terms of carrying out the analysis itself and in interpreting the results. The chapter's focus is principally on medium- and large-scale agro-industrial type biogas plants with automated feeding, active heat control, active agitation (or leachate recirculation) and technical application of the biogas (electricity, heat or upgraded biogas).

9.2 Energy demand of biogas plants

A broad range of different technologies for biogas plants are available on the market; the selection of a certain type of technology has a significant effect on the energy demand of the plant. For example, continuously stirred tank reactors (CSTRs) differ substantially from 'vertical garage door' dry batch digesters in terms of their electricity consumption (which is greater for the stirrers in the CSTR system) and their fuel consumption (which is much higher for a vertical garage door system mixed and fed by a wheel loader). The actual parasitic energy demand depends on the substrates and their pre-treatment, as well as on the treatment of the biogas and the liquid or solid residues. The energy demands associated with the different process steps in a biogas plant are discussed below. Precise standardisation is not possible, but all energy demand data will be referenced to the amount of biogas (typically with 55–60% methane content) in the unit kWh/m³ raw biogas.

9.2.1 Transport and storage

The transport and storage of agricultural substrates typically require relatively low energy inputs. The main energy consumption in this step is associated with fuel consumption by tractors, trucks and wheel loaders. This might be different in the case of centralised biogas plants or waste treatment plants where the transport of fresh and digested material might be significant (up to hundreds of kilometres).

In a few cases, the transportation of liquid substrates such as effluents and manure is carried out in pipeline systems, which require electricity for the pumps. During substrate transport and storage, heat demand is minimal and is only associated with substrates that enter a solid phase at low temperatures (e.g. fats) or to avoid freezing at low temperatures in cold climates.

As a proportion of the gross energy production associated with biogas, the energy demand for storage is extremely low. Both practical experience

and model calculations confirm that transport is not an issue in terms of energy demand, but is in terms of cost.

9.2.2 Substrate pre-treatment

Substrate pre-treatments are now becoming more common and in many cases are relatively energy intensive. Mechanical and thermal pre-treatment methods such as milling, grinding and heating require large amounts of energy. Some pre-treatment steps cannot be avoided (e.g. separation and crushing of wastes and sanitisation or even sterilisation); however, the energy demand can still be optimised. Typically, about 20% of the energy from the biogas may be required (mainly as electricity, with less required as heat) for the whole pre-treatment chain of source-separated organic municipal solid waste prior to fermentation.

When the purpose of the pre-treatment is an increased biogas yield (as promised by a large number of technology providers), extremely thorough verification tests are required. This type of technology often promises an increase of 5–20% in biogas yields; however, the energy demand for the pre-treatment can increase by the same amount. The effects achieved are heavily dependent on the substrates used and the fermentation technology adopted. Positive effects (such as shorter retention times in the fermenter or less mixing energy) can be obtained, but a detailed comparison between the energy demand and the expected yield increase must be undertaken. It is also advisable to investigate the practical experiences of other biogas plant operators who have used this technology.

9.2.3 Substrate supply to the fermenter and fermentation: electricity demand

The fermentation process itself is often the main source of energy demand, with pumps and stirrers representing the main consumers of electricity. Different fermentation technologies display significant differences in their parasitic electricity demand. For example, CSTRs and continuously mixed plug flow fermenters have relatively high electrical energy demands, while dry batch fermenters (such as vertical garage door fermenters) have very low electrical energy demand. The vertical garage door fermenters have a high fuel demand because of the wheeled machinery used for transportation in and out of the fermenters and for mixing outside the fermenters. However, batch systems offer lower biogas yields than CSTR systems (FNR, 2011).

The design of the plant as a whole has an important effect on the energy demand. For example, one-stage fermentation can have a lower energy demand, but is also likely to have a lower biogas yield than multi-stage

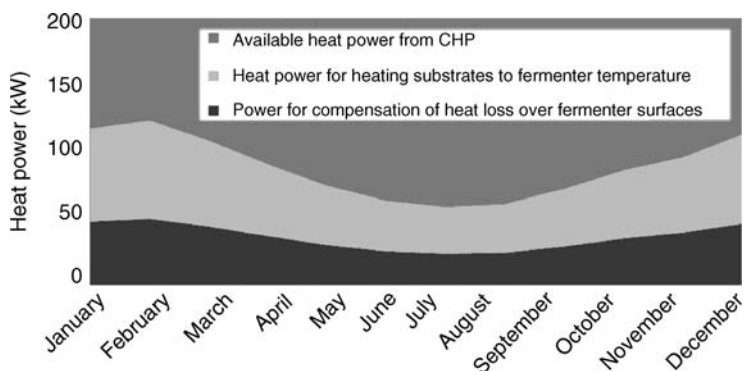
fermentation with a greater number of mixed and heated fermenters. Substrates in liquid form, such as slurries, require less energy for pumping and mixing than substrates with a high concentration of solids. This is balanced out by the higher biogas yield per unit volume offered by a system using more solid substrates.

Practical data obtained from German agricultural biogas plants that process mainly energy crops and excrements and produce between 100 and 1000 m³/h of biogas show variation in the electricity demand of the different plants. In the case of liquid feedstock such as manure, the electricity demand for biogas production (without gas utilisation) is between 15 and 23 kWh_{el} per MWh_{Hi} of biogas produced. For higher solid content feedstock such as energy crops, the electricity demand is slightly higher, at about 19–27 kWh_{el} per MWh_{Hi} of biogas produced (VDI, 2011).

9.2.4 Substrate supply to the fermenter and fermentation: heat demand

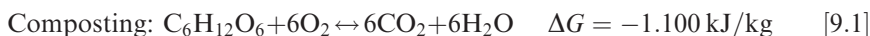
Heat input to the fermenters is required because the microorganisms are active at defined temperatures mainly above ambient. Ambient temperature changes with the seasons and thus the thermal energy input is variable. In addition, the choice of technology influences the heat demand according to the following parameters: use of mesophilic or thermophilic microorganisms; ratio between surface and volume of the fermenters; thickness and quality of insulation; and solids concentration in the fermenter. Under climatic conditions found in Central Europe, for agricultural mesophilic biogas plants using mixtures of manure, organic residues and energy crops, the process heat demand is in the range of 5–15% of the energy available in the biogas. When all biogas is locally used in a combined heat and power (CHP) unit, typically 20–40% of the heat from the CHP unit is required to heat the fermenters. During the planning stage, the thermal parasitic energy demand of a biogas plant requires detailed analysis that takes into account climatic conditions over the year. Figure 9.1 shows an example of the heat demand of a biogas plant. In summer, the heat demand is significantly lower than during the winter: in very cold climates the winter heat demand can be as high as or higher than the total heat produced by a CHP unit. A detailed analysis, and particularly one that takes account of the temperature of the substrates before entering the fermenters, is essential for successful biogas plant operation.

For biogas plants with high solid concentrations in the fermenters, self-heating at high external ambient temperatures has been reported. It should be borne in mind that anaerobic degradation is a slightly exothermic biological process. More than one degree Kelvin self-heating can cause



9.1 Example of heat demand for fermentation in a mesophilic fermenter: biogas is utilised in a CHP unit; substrates are manure and agricultural residues at a scale of 10 000 t per year; average heat demand is 45% of heat produced with a maximum of 62% in winter and a minimum of 30% in summer. The CHP is sized at 190 kW_{el} and 200 kW_{th}.

reduced microbiological activity and hence decreased biogas yields. In comparison with aerobic composting, only a small amount of energy is released, as illustrated by the following formulae.



Self-heating in a fermenter is caused firstly by the exothermic anaerobic process from formula 9.2; however, it is very unlikely that the phenomenon is caused by this process alone. Due to the fact that self-heating is related to a high level of fermentation of solids, and to the feeding of dry substrates, two additional effects are probably responsible. Within the dry substrates, air is fed into the fermenter, causing aerobic processes with high heat production, as described by formula 9.1. In addition, when there is a high solid content in the fermenter, heat conductivity is low, which hampers heat transfer from the fermenter to the outside. In the case of high fermentation of solids, especially in hot seasons or regions, measures must be taken to minimise self-heating. Such measures include compacting substrates before feeding (to avoid oxygen entering the fermenter) and soaking the substrate with fermenter liquids or water before feeding. The use of a thermophilic process can also ensure a temperature gradient between the fermenter and the external environment for cooling purposes. Finally, active cooling of the fermenter can be an additional measure.

9.2.5 Gas utilisation in CHP units

When the main role of a biogas plant is electricity production, the second most important source of energy consumption is the CHP unit. The CHP consumes no heat; it is in fact the main ‘producer’ of heat in the form of waste heat from the exhausts and the cooling water cycle. However, the unit consumes not insignificant amounts of electricity during operation. Typical values taken from German biogas plants show an electricity demand of between 7.5 and 15 kWh_{el} per MWh_{Hi} of biogas produced for a range of different CHP units. More important is the provision of effective cooling in the cooling water cycle of the unit. If this cooling is necessary for all the heat produced, the electricity demand will be at the upper end of the range. In addition, transport losses must also be taken into account: these occur both in cables between the CHP and the final consumer or the electricity grid and in transformers.

9.2.6 Upgrading of gas to natural gas quality

Gas upgrading mainly involves the removal of carbon dioxide from the biogas. This process is typically energy intensive and the energy demand depends to a large extent on the technology used. The main source of energy demand for all technologies is electricity, mainly for the operation of compressors or pumps. The typical electricity demand for water scrubbers, pressure swing adsorption and the majority of membrane technologies is between 0.2 and 0.25 kWh_{el} per m³ of raw biogas. For chemical absorption processes, the electricity demand can be lower but there is an additional heat demand of up to 0.4 kWh_{th} per m³ raw biogas, depending on the technology used. The energy consumption may also be influenced by further use of upgraded biogas. Electrically driven compression may be required for injection into gas grids (which typically operate at pressures of between 4 and 80 bar) or for supplying a vehicle filling station (which requires pressure of up to 300 bar). For vehicle fuel supply, the energy demand for additional compression has to be taken into account: this ranges from approximately 0.2 up to 0.35 kWh_{el} per m³ of biomethane. The lower value applies for compression of the gas from the 30–40 bar supplied by the grid up to 300 bar; the upper value is for compression all the way from 1 to 300 bar. The typical requirement is for compression from 1 to 250 bar, for which 0.31 kWh_{el} per m³ of biomethane is required. The heat generated by most biogas upgrading technologies, especially from compressors, can be recovered at temperatures between 50 and 100°C and can be used, for example, for fermenter heating. This can be considered as a method of supplying energy to the biogas plant.

9.2.7 Post-processing, storage and transportation of residues

Last but by no means least, further processing of liquid and solid residues can give rise to an energy demand. Liquid residues usually leave the fermenter by gravity into a storage tank. For the purposes of storage pumping, transportation (by pipes or by tanker lorry) and mixing (homogenisation before pumping out of a storage tank) can demand electricity or transport fuel depending on the local situation. Compared with the total energy demand of the whole biogas plant, this energy demand is usually very low. It only becomes significant when further processing of the liquid or solid residues is employed for solid/liquid separation or for pellet production and water purification. For solid/liquid separation of residues from fermentation, Arndt and Wagner (2009) report an electricity demand of about $1.2 \text{ kWh}_{\text{el}}$ per kg of wet residue. Further drying before pelletisation requires about $1.5 \text{ kWh}_{\text{th}}$ plus $0.05 \text{ kWh}_{\text{el}}$ per kg of residue, for a residue with 20–30% dry solids (Arndt and Wagner, 2009). Subsequent pelletisation can require between 0.25 and $0.35 \text{ kWh}_{\text{el}}$ per kg of dried residues (Arndt and Wagner, 2009). There is a further electricity and heat demand for processing of the liquid phase after separation, but the typical energy demand values cannot be established due to the diversity of processes that are employed; these technologies are, in any case, not yet widely used.

9.2.8 Process control equipment and infrastructure

The amount of energy required for the operation of process control equipment and infrastructure depends on the local situation. Process control typically has a low electricity demand in most biogas plants. The energy demand of the infrastructure is also typically low, but can be significant in terms of heat as well as electricity if offices and visitor facilities are frequently used, or if 24-hour operation of the plant requires large lit areas. The local conditions in this respect must therefore be taken into account in the evaluation of the energy demand involved in process control and infrastructure.

9.3 Energy supply for biogas plants

The provision of energy supply for a biogas plant is an important issue that affects both the economics of the project and the ecological footprint of the plant. It is therefore advisable to gather as much information as possible on the energy demands of the plant before planning the energy supply. The minimum information necessary in this respect is

- maximum energy demand (e.g. simultaneously running electrical equipment; starting load of pumps/stirrers/CHP; maximum heat demand in winter)
- time dependency of energy demand (e.g. changes dependent on season, over the course of a week and over the course of a day)
- heat level(s) required
- definition of single energy consumers with behaviour as described above.

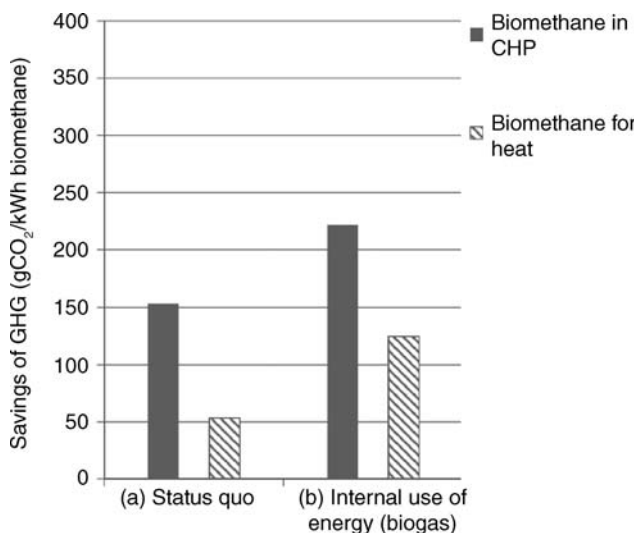
The provision of energy supply can then be planned on this basis. The first issue to be determined is how much of the energy demand is to be met by external sources (e.g. grid, generator, heating unit) and how much by internal resources (e.g. biogas burner, excess heat from single aggregates (compressors or CHP unit)). It is generally possible to run a biogas plant isolated from energy grids, but running the plant within an electricity grid is more convenient. The final solution for energy supply is determined not only on the basis of technical and economic optimisation, but increasingly also on ecological optimisation: today, the aim of reducing the greenhouse gas emissions of a plant is an important aspect in the project planning process. A biogas plant that is able to meet its own energy demand with biogas or alternative renewable energy has a significantly better greenhouse gas balance than a biogas plant supplied with fossil energy (e.g. from the electricity or heat grid). An example is shown in Fig. 9.2.

9.3.1 Electricity supply

For most equipment used in industrial-scale biogas plants, a reliable electricity supply is essential for correct operation. Electricity supply has to be continuous and at a very uniform voltage, due to the fact that most plants are controlled by a computer-based central control unit. If a reliable electricity supply cannot be guaranteed, the electrical equipment selected must be able to operate with the available supply; alternatively, additional technical measures must be undertaken, such as the use of batteries or the implementation of an uninterruptable power supply.

The main parameter for the electricity supply is the maximum instantaneous load, which is in most cases connected to the starting current of the motors (for example in pumps and mixers it can be as much as double the power demand for each single piece of equipment). The simultaneous starting and running of multiple units of equipment must also be taken into account.

The simplest method for providing electricity supply is a connection to an existing reliable electricity grid with sufficient capacity for the maximum load of the biogas plant. The electricity for most biogas plants in Europe is



9.2 Visualisation of the greenhouse gas balance for use of upgraded biogas (biomethane) for electricity supply or heat supply. Status quo (a) assumes that the energy is supplied from electricity mix (Germany) and heat from natural gas /heat pump (b) shows the greenhouse gas balance for the same biomethane production plant calculated assuming that the energy is supplied from biogas. For each, the substrate is assumed to be energy crops (adapted from Thrän *et al.*, 2011).

supplied in this way. In order to reduce the maximum load of the biogas plant, the control devices can be programmed so that single components are never turned on at the same time. If a grid connection is not possible, or is unreliable, the electricity can be supplied by a biogas-driven local CHP unit. In this case, a unit designed for a grid-independent start, known as a self-triggered unit, is necessary. A gas reserve is also required when biogas production is low and for use when the biogas plant is initially put into operation when no biogas is being produced. The gas supply can be obtained either through a natural gas grid connection or through the use of pressurised gas or liquefied gas (LPG) in bottles or a tank. The CHP unit must be correctly designed to operate under these conditions; alternatively a dual-fuel CHP unit can be used, which can run on diesel in situations when no biogas is available.

Electrical energy losses occur mainly in cables and connectors: the length of cables should therefore be minimised. Transportation losses of electricity within a biogas plant can amount to around 1–3% of the energy exported. Further energy loss can occur in a transformer for different voltages, typically at the connection point with a local grid. Losses of between 1 and 3% have been documented; the main factor affecting these is the choice of equipment. Thus, a transformer must be selected that can guarantee low

losses; this must be designed for the real expected load that offers optimum efficiency during operation. An existing transformer with low efficiency or a very high load cannot be the best choice from an economic perspective.

9.3.2 Heat supply

A heat supply is necessary to maintain a constant temperature for fermentation and for substrate pre-treatment processes such as sanitisation. For these purposes, low temperatures of below 100°C are necessary and a standard heat supply such as space heating is sufficient. For planning purposes, the highest heat load must be determined from the heat demand for

- heating fresh substrates
- compensation of heat losses from the fermenter surfaces
- heating of buildings and biogas plant equipment (e.g. to avoid freezing).

This heat demand should usually be determined for the coldest season of the year. Alterations in substrate composition must also be taken into account.

A continuous heat supply must be guaranteed so that the fermentation temperature can be kept constant. The temperature should be kept at a steady level, avoiding deviations of more than $\pm 1\text{K}$. A continuous temperature change of more than $\pm 1\text{K}$ over about ten days will have a negative impact on the biological balance that drives the fermentation process (VDI, 2011). The heat supply must therefore ensure that this type of temperature fluctuation does not occur, although short interruptions in the heat supply can be tolerated.

The heat supply itself can be based on the combustion of biogas or can come from a local CHP unit in the form of waste heat. When either of these two methods are employed, an alternative gas supply is required at the start of the plant operation and at times of low biogas production: this can come from natural gas or from bottled, compressed or liquefied gas. An alternative method is for heat to be supplied from heating systems based on renewable (e.g. pellets) or fossil (oil, coal) sources or via a connection with a local heat grid.

In some cases, higher temperatures or steam may be required, for example when a steam explosion process is applied for substrate pre-treatment or thermal regeneration of a chemical adsorbent is required during biogas upgrading. Steam can generally be supplied by direct biogas combustion processes or by an exhaust heat exchanger from a specially equipped CHP unit (often called de-coupling of heat). If this is impossible, then external steam production is required. For detailed planning, the steam parameters and the technology required for steam generation must be fine-tuned.

The heat for the fermentation processes can be supplied internally or

externally to the fermenter. An internal heat supply is obtained with stainless steel or polypropylene heat pipes located either in the fermenter or in the fermenter walls. Electrical energy is required to circulate only the hot water between the heat source and the fermenter. Depending on the construction and the substrates used, heat transfer from the heat pipes into the fermenter can be impeded by deposits on the pipes or the fermenter walls; in this case, the fermenter must be opened to allow the pipes to be cleaned. An external heat supply is obtained with external heat exchangers in which water on the primary and secondary side must be circulated, requiring more electrical energy than an internal heat supply system. The advantage of external heating is the ability to clean and maintain the heat exchangers without opening the fermenter.

Energy losses in the form of heat occur in hot water pipes, connectors and heat exchangers, and are mainly determined by the quality of insulation. Depending on the length of pipes and the technology used in the heat exchangers, these losses can amount to up to 10% of the total heat supplied. The choice of heat exchanger technology has a particularly significant influence on heat losses.

9.3.3 Fuel supply

Fuel might be used to operate dual-fuel CHPs or external generators. In some countries (e.g. Germany), legal requirements dictate that renewable bio-oils should be used for dual-fuel CHP units. In most cases, fuel is necessary to operate mobile equipment, generally wheel loaders, tractors and transport vehicles. Fuels are usually bought locally and stored in tanks at the biogas plant. Diesel (fossil diesel or biodiesel) fuels are used for most applications. As an alternative, upgraded biogas can also be used for the majority of applications. This requires an upgrading unit at the biogas plant and high-pressure storage (200–300 bar), as well as a pump for filling vehicles. The mobile equipment must also be able to run on natural gas (upgraded biogas has to meet the same requirements as natural gas). Unfortunately, only a few natural gas tractors and transport vehicles are available commercially. Long-distance transportation and complex logistics lead to high fuel consumption and should be avoided by careful planning during the design stage. It is also important to avoid running equipment at no-load.

9.4 Balancing energy flows

Due to the fact that efficient energy use is one of the key challenges for biogas plant optimisation, a detailed analysis of the energy flows can show possible areas for operational and technological improvements. An energy

balance can therefore be carried out when the energy-producing and energy-consuming devices have been established. On the basis of a detailed energy balance, the different technological options can be evaluated and compared. This section explains the basics and framework of energy balancing, along with a specific example.

9.4.1 Basics and definitions

Independent evaluation of the energy flows in a biogas plant requires a clear methodology and definitions. The crucial methodological issues are as follows.

- For an exact calculation of an energy balance for a single biogas plant, the correct boundaries have to be defined and correctly taken into account. All flows of energy and material into, out of and within the biogas plant must be described and all the boundaries correctly defined, including the point of substrate import into the biogas plant, the point of liquid/solid product output (e.g. including or excluding logistics), the point of energy input (e.g. electricity before or after a transformer) and the points of energy output. These should not be defined solely on the basis of a flow diagram; instead, definitions should be established at the plant itself, for example at a pipe connector. This is of particular importance when comparing different biogas plants. It has to be clearly stated which individual processes belong to the biogas plant and which processes do not. The question of what equipment is necessary for biogas production and what equipment is necessary for processes external to the biogas production can help to identify suitable boundaries.
- The calculation method for analysing the energy content of solid, gaseous and liquid material streams has to be established, particularly with respect to chemically bound energy. One promising option is the measurement or calculation of the heating value of the material flows.
- The definition of references for the purpose of benchmarking and evaluation in comparison with alternative technologies is extremely important and helps to define suitable boundaries. Starting with available data relating to the alternative technologies can be helpful for methodological clarification.
- The general rules for process modelling must be taken into account. This implies the use of sound and consistent variables and units that are always in correlation with the same reference. A reference can be a time unit (e.g. day, month, year) or a mass unit (e.g. 1 t of substrate input). Moreover, the main rules for energy balancing are the fundamental theorems of energy. At the very least, the first theorem – in a closed

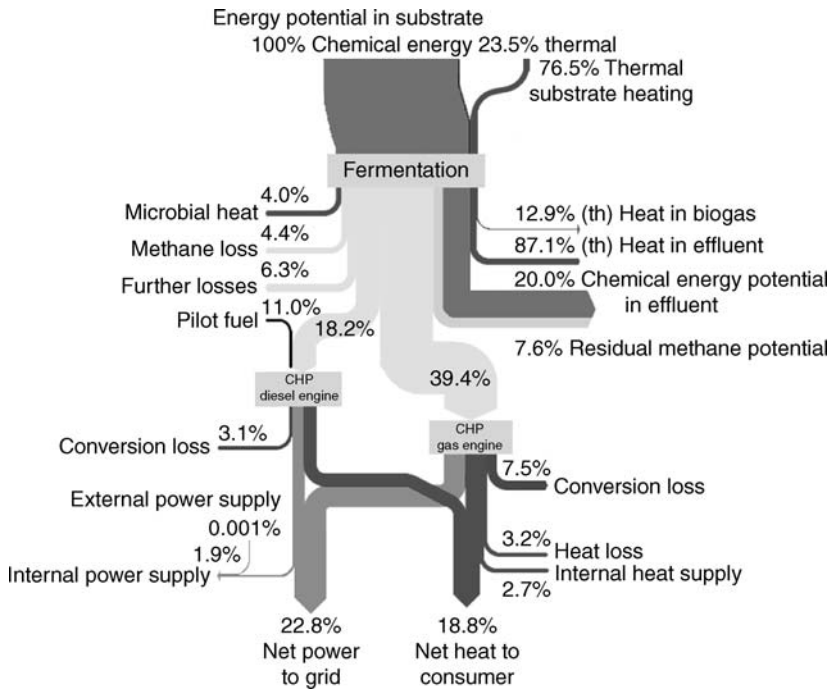
system, energy cannot be lost, only transferred – must be taken into account when defining a calculation model.

- To keep track of the energy flows it can be helpful to separate the model for the whole biogas plant into sub-models of single units of the plant. This can be carried out on the basis of the process steps defined in Section 9.2, but different segmentation can also be used. Most important is application of the rules for the whole balance to each sub-model to guarantee a consistent methodology.
- Last but not least, the method for addressing energy ‘losses’ at the different stages in the process must be specified. Firstly, ‘losses’ in this context must be defined. One suggestion in this regard is that all energy flows over the system boundaries that cannot be used for practical applications can be classified as losses, including conversion losses that occur as frictional heat. Moreover, each biogas loss (e.g. via security valves, un-combusted methane in the exhaust of a CHP unit or a flare) can also be defined as an energy loss from the system. However, it should not be automatically assumed that all differences in the calculated energy balance that are unaccounted for actually equate to true losses.
- Data collection will be one of the challenges for successful balancing. Most data are not readily available and require careful measurement. It must be remembered that the energy uptake of technical units and process steps is dependent on the load and in most cases does not correlate with the data provided by the equipment supplier. For example, motor-driven equipment is very rarely operated at full load and thus the energy demand is typically 50–70% of the energy demand given in the technical specification. Additionally, most devices are only operated for an average of a few minutes in every hour.

9.4.2 Practical balancing

Once the system and boundaries have been clearly defined and the necessary data collected, an energy balance evaluation can be carried out. An example of the energy balance of an agricultural biogas plant connected with a CHP unit for electricity and heat production is given in Fig. 9.3.

In Fig. 9.3 it is clear that a very large proportion of the energy chemically bound in the substrates will not be available for external use. In this case, about 40% is available as electricity and heat. The chemically bound energy that is not converted into biogas is retained in the solid and liquid residues, and offers little potential for methane production. The energy flow diagram clearly indicates the different pathways of ‘losses’ of energy from the system. These energy flows must be the starting points for process optimisation, with measures undertaken to



9.3 Flow diagram of the energy balance of an agricultural biogas plant connected with CHP for electricity and heat production (Fischer *et al.*, 2009).

- increase the biogas yield in order to thereby decrease the methane production potential of residues
- make use of the thermal energy in the effluents (e.g. by using a heat exchanger or heat pump)
- avoid methane losses (e.g. avoid high pressure during gas storage, which leads to operation of the security valves; avoid leakages through detailed searches for single leaks)
- avoid 'further losses', including operation of the flare (e.g. better tuning of gas production and gas utilisation by optimising the management of the substrate feed)
- decrease conversion losses and the energy demand of the plant itself (e.g. use of more efficient equipment and adjusting the parameters of the existing equipment to ensure operation at maximum efficiency).

9.5 Conclusion and future trends

It has been shown that a thorough understanding of energy flows in a biogas plant offers great potential for the optimisation of plant operation, leading

to reduced energy demand, more economical operation and better ecological performance. Modelling and balancing of energy flows in a biogas plant give a clear insight into the processes involved and allow the identification and implementation of measures to optimise the behaviour of the plant. It is then possible to identify the best technology and management options for a biogas plant based on the local conditions at low cost, prior to installation and operation. In practice, however, this evaluation is seldom carried out. Moreover, the best option for the end use of the biogas produced can also be determined (e.g. for electricity, heat or upgraded biogas) and alternatives evaluated. In particular, the best choice can be made for each step in the process: for example, for the energy supply of a remote energy consumer, the option of a heat pipe or gas pipe with combustion can be compared with the option of CHP at the location of the energy consumer.

It is assumed, therefore, that energy modelling and balancing will prove extremely important in the future design of technologies for use in biogas plants. Moreover, the best management methods for practical operation of biogas plants can be identified and guidelines for plant operators drawn up. Last but not least, steadily increasing environmental demands on biogas plants can be addressed using the methods described in this chapter, both during the conception and planning phase of new plants and during renovation of existing biogas plants.

The modelling and balancing of energy flows in a biogas plant requires considerable effort. However, this detailed analysis alone makes it possible to achieve goal-oriented optimisation of a biogas plant: the need for extensive research and the application of a detailed methodology should not therefore be considered an insurmountable obstacle. Experience has shown that all the required work and expenditure will achieve long-lasting positive benefits, both economic and environmental. Scientific support can be offered to plant operators to enable them to make efficient investments in both time and money to this end.

9.6 Sources of further information and advice

Scholwin and Edelmann (2009) describe the full process of biogas production from solid as well as liquid residues, agricultural by-products and energy crops. This book will soon be available in English. Data on the energy demand of biogas plants and their components are measured and evaluated in measurement programmes. The best known comprehensive overview of the energy demand behaviour of biogas plants was carried out by Prof. Peter Weiland (FNR, 2011); it is available both as a book with analysis and as a separate data collection at www.fnr.de, where it can be downloaded in German and Russian. Information on the modelling, evaluation and energy balancing of biogas plants is often related to life cycle

analysis, detailed descriptions of which can be found in the literature (DBFZ, 2009; Arnold, 2011).

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Abstract: Efficient monitoring and control of anaerobic digestion (AD) processes are necessary in order to enhance biogas plant performance. The aim of monitoring and controlling the biological processes is to stabilise and optimise the production of biogas. The principles of process analytical technology (PAT) have been identified as some of the most promising on-line facilities for monitoring and controlling heterogeneous bioconversion processes. The future trend is to keep procedures as simple as possible, but to have available on-line monitoring systems with early warning strategies for plant operators, which would help to avoid significant process disturbances. The general aim is to move the processes efficiently towards their theoretical maximum. Mathematical modelling of AD is another method to help control the process and avoid significant instabilities during fermentation. Such models can improve the understanding of biological processes.

Key words: anaerobic digestion, process monitoring, on-line process control, process analytical technologies, mathematical modelling.

10.1 Introduction

Some of the most efficient biogas plants run on controlled mixtures of feedstocks using co-digestion processes. On the other hand, very heterogeneous biomass feedstocks are challenging from a biogas plant process control perspective. Digestion of single substrates, such as a single source of pig or cow manure, produces a low biogas yield due to the lack of energy-rich organic substrates, often a lack of carbon sources. Nutrient deficiency in single substrates can be balanced when co-digesting multiple feedstocks.

Carbon, nitrogen, phosphorous and sulphur must be present in the mixture in optimal proportions; trace elements must also be present in adequate amounts, above certain threshold concentrations as well as below toxic levels, for the microbial processes to perform satisfactorily (Angelidaki, 2002).

The anaerobic digestion (AD) process has to become a much better controlled process in the near future in order for biogas and biomethane to gain a significant market share on the global energy scene. Even though AD involves very complex and heterogeneous substrates, process analytical technology (PAT) tools show promising prospective possibilities of being able to serve as robust on-line monitoring and management tools. The monitoring must be performed in real time and must be essentially non-invasive in order to provide the needed insight into the process while at the same time it must be effective and practical, especially in small- to medium-scale plants. The AD process and biogas production are increasing in importance. The AD sector is able to provide major biotechnological solutions for European energy demands. Biogas production capacities in Europe reached eight million tons of oil equivalent (toe) in 2009 (EurObserv'ER, 2010). The target for biogas is one third of all bioenergy consumption in the EU, 15 million toe in 2015 (Holm-Nielsen and Oleskowicz-Popiel, 2007). Biogas production has the potential to be one of the most flexible and adjustable energy sources and at the same time takes care of very problematic organic wastes and substrates. If organic waste is used incorrectly it has major negative impacts on the water environment, human and animal health, and air quality.

10.2 Process analysis and monitoring

10.2.1 Basic process analysis

Biological substrates – the biomass feedstock for biogas production – are very heterogeneous by nature, and the AD process is a highly complex multi-phased process. Process control has been developed and introduced in the AD process in recent decades and the analysis tools are becoming increasingly user-friendly over time. AD consists of several biochemical steps catalysed by a mixture of microorganisms; thousands of different species of bacteria are involved. The main steps are hydrolysis, acidogenesis, acetogenesis and methanogenesis. The various steps of AD are highly complex, but take place simultaneously when handled with good management at the biogas plants. The limiting step can be hydrolysis if there is a lot of material that is difficult to digest, solid organic and particulate material like maize silage. On the other hand, when uncomplicated fermentable feedstock is available, the accumulation of acids can occur and methano-

genesis becomes the rate-limiting step (Borjesson and Mattiasson, 2007). Examples of parameters that affect the various steps in the AD processes to various degrees are the composition of the input materials, various pre-treatment of feedstocks, feeding rate and temperature control of the process (Mata-Álvarez *et al.*, 2000; Angelidaki, 2002).

A fine balance must be maintained between these groups of bacteria and processes to secure a productive yield. In the case of process imbalance, an accumulation of hydrogen or other intermediates is likely to occur that would result in inhibition and metabolic shifts (Legin *et al.*, 2003). Process imbalances normally have three major causes: hydraulic overloading, organic overloading or the presence of inhibitory concentrations of toxic materials in the reactor such as ammonia and heavy metals (Legin *et al.*, 2003). Proper understanding and manipulation of these stages and their respective intermediates or products is the key to suitable monitoring scheme solutions for the biogas plant.

10.2.2 Basic process monitoring

Currently, many biogas plants neither continuously measure processes in depth nor utilise in-depth process data when they have been generated. In rare cases, data are collected, but only intended to serve as routine monitoring and control of parameters rather than for real-time process control. Often, process control in these plants is limited to daily evaluation of easily measurable parameters such as temperature, pH or biogas production rate, volume and quality. Additionally, at regular intervals (weekly or monthly) off-line measurements are carried out for total suspended solids, volatile organic acids, ammonia nitrogen and volatile fatty acids (VFAs). The number of measurements is often limited due to the high costs of chemical analysis, time consumption and lack of trained personnel. However, even with recent development of less expensive laboratory analysis such as fast photometric tests for ammonia nitrogen and VFAs, these measurements cannot give a fast response to facilitate process imbalances during the AD process. The AD process is continuous – there is no on-and-off button like at natural gas grid connected systems.

10.2.3 Advances in process monitoring

More sophisticated and robust techniques are required for on-line and continuous monitoring of fermentation. Such innovative solutions would provide a better control tool, increase the stability and yield possibilities of the process, and allow the fermentation process to run at more optimal conditions. It would effectively increase the economy of biogas plants.

In order to meet increasing economic and technical operational targets,

optimisation of the process capacity can only be done by applying advanced on-line monitoring; by identifying chemical and physical parameters, this gives an early warning of process imbalances and ultimately leads to improvements in plant efficiency. The monitoring tools must be robust, technically as simple as possible and require little maintenance in order to be of interest for the biogas sector.

Anaerobic digestion can be monitored in different process stages from supply chain until final stage of produced biogas: substrate quality and its biogas potential can be monitored by measurements of solids, TS (total solids) and/or volatile solids (VS) or chemical oxygen demand (COD) and their degradations during the process; intermediate products formation (VFAs, H_2 , CO , NH_4^+) and their influence on alkalinity and pH; and final product formation by the overall biogas production or CH_4/CO_2 rate. Typically, for biological processes, microbial communities and activities are also of interest (Boe, 2006).

Temperature and pH measurements are key quantifications and are compulsorily monitored by all biogas plant operators to ensure a suitable environment for the bacteria consortia. These are currently the most widely measured real-time parameters at biogas plants, usually determined using simple electronic pH meters and temperature sensors embedded in the digester, but where to measure correctly to give a true picture of the process is an interesting issue. Maintaining a constant system temperature is of critical importance because of the strong influence of temperature on the AD process from a kinetic and thermodynamic point of view (Kim *et al.*, 2002). Temperature fluctuations can adversely affect the digestion process, especially for plants operating at thermophilic temperature ranges.

10.2.4 Monitoring the produced biogas

The most important measurement for biogas plant operators, from the production point of view, is biogas volume. Biogas production measurements can be expressed as overall biogas production or as methane yield, since methane is the valuable product. These measurements only inform as regards to the end-product (the produced biogas) without giving any information about biological process such as imbalances occurring during the previous biochemical stages. A low recorded biogas or methane yield would only give an indication that the fermentation was disturbed. For instance, a perm-selective gas sensor for determining the composition of carbon dioxide/methane mixtures in the range 0–100% is described by Rego and Mendes (2004). With a time response of less than 1.5 minutes, such a control will make it possible to optimise the operating conditions of the methane recovery units, but not the fermentation itself. Measurement of the exact gas composition might give some valuable information about the

process stability and efficiency. The ratio between CH_4 and CO_2 is usually stable during the process; it might nevertheless change when the anaerobic fermentation is disturbed. This is because the ratio also depends on other factors such as substrate quality and composition, process temperature and pH.

10.2.5 Biogas production in wastewater treatment plants

In cases where biogas production is not the main aim of implementing the anaerobic digestion process, i.e. in wastewater treatment plants, organic matter removal is an important indicator. The effectiveness of the process can be expressed as TS, VS, COD or biological oxygen demand (BOD) removal (El-Gohary *et al.*, 1999; Perez *et al.*, 2001; Steyer *et al.*, 2002). The BOD gives important information about easily biodegradable organic substances, which can be correlated to total biogas production. However, in samples with a significant content of organic polymers, polysaccharides, fats and proteins, underestimation of BOD may occur (Liu *et al.*, 2004).

10.2.6 Volatile fatty acid monitoring as a useful process control tool

Organic overloading can be defined as an input of COD that exceeds the degradation capacity of the microorganisms (Moletta *et al.*, 1994). This parameter can also be measured to ensure effective substrate feeding of the reactor. Volatile fatty acids (VFAs) are intermediates that may accumulate during the fermentation process; they thus become the first indicator of anaerobic digestion imbalance (Punal *et al.*, 2003). VFA measurement can be a very useful tool for process monitoring both in low and high buffered systems, whereas pH and alkalinity can be only applied to the first type. VFAs measurement seems to be the best parameter for indicating instabilities since the concentration of these compounds gives a signal on the state of the internal environment and progress of the digestion process. Each individual component of the VFAs can give valuable information and become an indicator for early warning of process imbalances. Different researchers have suggested a diverse choice of acids as an indicator of stress level in the event of a failure in the AD of biomass: iso-butyric and iso-valeric (Hill and Bolte, 1989) and n-butyric and iso-butyric (Ahring *et al.*, 1995). Propionic acid may also be a process indicator. During overloading, when the partial pressure of hydrogen increases, the degradation of propionate is affected before other VFAs (Boe, 2006). Hansson *et al.* (2003) proposed the use of propionate as a process indicator, and the ratio of propionic to acetic acid was found to be viable and a sensitive indicator

for AD instability by Marchaim and Krause (1993). VFA concentration is an excellent parameter for early indication of organic overloading and is easily measured by gas chromatography or high-performance liquid chromatography after all particulates are removed from the sample (Holm-Nielsen *et al.*, 2008). Pind *et al.* (2003) presented a novel in-situ filtration technique for animal slurry or manure. An on-line headspace gas chromatographic method was described by Boe *et al.* (2005, 2010).

10.2.7 Other important analytics and process information

Besides VFAs, the measurement of alkalinity has also proved to be useful in the on-line monitoring of the fermentation process. A correlation between VFA accumulation and alkalinity levels was presented by Hawkes *et al.* (1994), who suggested that the monitoring of bicarbonate alkalinity would serve as an effective tool for early warning of organic overloading. Increased concentration of VFAs will consume alkalinity before changes of pH are noticeable, and it is thus an alternative to pH measurements for well buffered systems (Lahav and Morgan, 2004). Some researchers suggest measuring the ratio of VFAs to bicarbonate alkalinity (VFA/ALK): the lower the ratio, the better is the balance of oxygenic and methanogenic bacteria (Barampouti *et al.*, 2005).

Other parameters that might be considered in developing biogas process monitoring schemes include ammonium. Although considered a nutrient, the compound in its un-dissociated form of 'free ammonia' can become toxic and inhibitory to the fermentation process at some concentrations depending on the pH (Koster, 1986) and concentrations could therefore be monitored. Likewise, depending on pH and alkalinity conditions of the system, the concentrations of hydrogen sulphide can exhibit a similar effect. O'Flaherty *et al.* (1998) describe hydrogen sulphide toxicity threshold alkalinity values from 200 to 500 mg/l.

Appropriate process information regarding the anaerobic digester process (biomass, substrates, intermediates, digestate and nutrients) not only facilitates making better control decisions but also optimises productivity, in turn leading to decreased variability and potentially improved biogas quality. Utilisation of diverse substrates and demand for high biogas yields requires highly efficient process optimisation. Several on-line techniques are well described in the literature (Vanrolleghem and Lee, 2003; Steyer *et al.*, 2006; Holm-Nielsen, 2008).

A growing number of biogas plants in Europe have shown an increased interest in on-line monitoring and control. This has led to more focused research to be carried out in the field of instrumentation, control and automation of anaerobic processes.



10.1 Illustration of full-scale PAT studies 2007–2010. Trials and tests were conducted at LinkoGas a.m.b.a., Lintrup, Denmark. PAT tools for on-line monitoring facilities were mounted in a recurrent loop integrated with fermentor no. 3, volume 2400 m³. Testing of various NIR probes (transflexive and reflexive) was conducted. The lower right-hand photo shows the sampling point for chemical reference analysis.

10.3 Optimising and implementing on-line process control in biogas plants

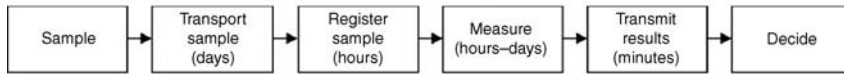
10.3.1 Efficient monitoring and control of the anaerobic digestion process

Efficient monitoring and control of fermentation processes including AD are necessary in order to enhance plant performance. The task of monitoring and controlling biological processes is to stabilise and optimise the production of biogas. Another important factor is to increase production capacity and speed without running any risk of process instability or inhibition and, finally, to enhance productivity. By applying process analytical technology (PAT) principles, the above issues can be addressed effectively (Fig. 10.1) (Junker and Wang, 2006; Mortensen, 2006; Holm-Nielsen, 2008; Madsen *et al.*, 2011).

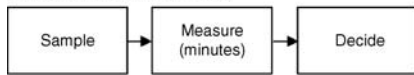
10.3.2 Process analytical technologies (PATs)

To facilitate continuous process improvement and optimisation of productivity and product quality, process data can be monitored and analysed at whatever resolution found necessary. Process analytical technology (PAT) represents the right measurement program and technologies for achieving these goals. PAT was primarily directed towards the pharmaceutical fermentation and processing industry, but the initiative is

Centralised laboratory strategy



Process analytical strategy



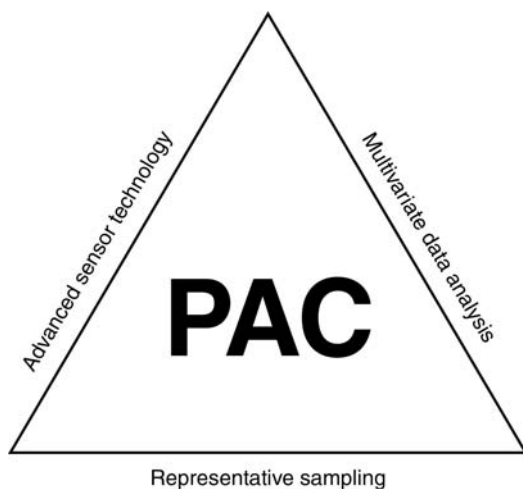
10.2 Comparison of analytical strategies for process monitoring.

also widespread in other industries. In 2005, the US Food and Drug Administration produced industry guidance in which PAT was defined as a system for designing, analysing and controlling manufacturing through timely measurements during processing of critical quality and performance parameters of raw and process intermediates (FDA, 2005). The goal is to monitor and control the process on-line as early as possible in the process and in real time at strategically selected process locations with steps that ensure the quality of the final product. The term ‘analytical technology’ in PAT refers to analytical chemical, physical, microbiological, mathematical, data and risk analysis conducted in an integrated manner. The term ‘quality’ of a product has the meaning of the final quality of various industrial processes; it can either be the concentration, pureness, strength, or similar of the processed products. According to the FDA guidance ‘Quality cannot be tested into products; it should be built-in or it should be by design’. Product quality and/or quantity have to be optimised during the ongoing process.

10.3.3 Control strategies: central laboratory versus on-line control

Traditionally, monitoring and quality control of production processes has been based on a centralised laboratory approach. Samples are collected from a process stream and sent to an analysis laboratory where sub-sampling, sample preparation and chemical analyses are carried out, often in an optimised manner, allowing multiple samples to be analysed in the same run. The time span for the primary sampling was taken from the point of the process stream until the analytical result had been produced and approved; this could span from several hours to days depending on the laboratory infrastructure and routine (Mortensen, 2006) (Fig. 10.2).

It is clear from Fig. 10.2 that the analytical strategy has to be changed from the centralised laboratory approach to the process analytical strategy if the biogas plant operator wants to benefit from the analytical results and use them as true process regulation parameters instead of just ‘delayed’ quality control parameters. In fact, the quality control task is moving from the



10.3 Fundamental disciplines of process analytical chemistry.

reference laboratory and into the process line itself. This can be considered as a change of paradigm (Junker and Wang, 2006).

10.3.4 Handling of complex and multiple data sets

Multivariate data analysis programs and process analytical equipment such as fibre optics and spectrophotometers at cost-efficient levels now allow for at-line and on-line techniques to enter the market for process monitoring and control in industries like biorefineries and biogas plants. The process analytical chemistry (PAC) approach, measuring on-line TS, VS, VFA and pH among other parameters, offers many advantages over traditional process characterisation. It is essential that the plant operator can read the state of the process continuously and launch correcting countermeasures as soon as possible, fully automatically in the future. It is important to move this step forward in the early stages of understanding biological processes and not to rely only on accumulated human-operator experience. PAC is based on three fundamental disciplines, as illustrated in Fig. 10.3 – representative sampling, process sensor technology and multivariate data analysis.

PAT implementation is multidisciplinary in its approach; fundamental understanding of correct sampling is one of the basic pathways not yet fully understood and integrated in various fermentation industries. Other central challenges for the successful development of on-line process monitoring of advanced biological processes involve the right choice of sensor technologies, reference analysis, multivariate data analysis (see Section 10.3.7), spanning of data, and model development and maintenance (Bakeev, 2010).

The incentive for a process analytical strategy, whether it is based upon PAC or PAT, is to increase and stabilise production yields by minimising all types of variations and keep the process within optimal operation conditions at all times. The process analytical approach will reduce the need for accurately determined analytical results from quality control laboratories, but it will never eliminate the need for those analyses completely. In the future, there will be a need for regular quality control and tests to run advanced PAT monitoring process control systems on-line. The two analytical strategies should, in fact, be viewed as complementary strategies.

10.3.5 Sampling issues in the context of AD process control

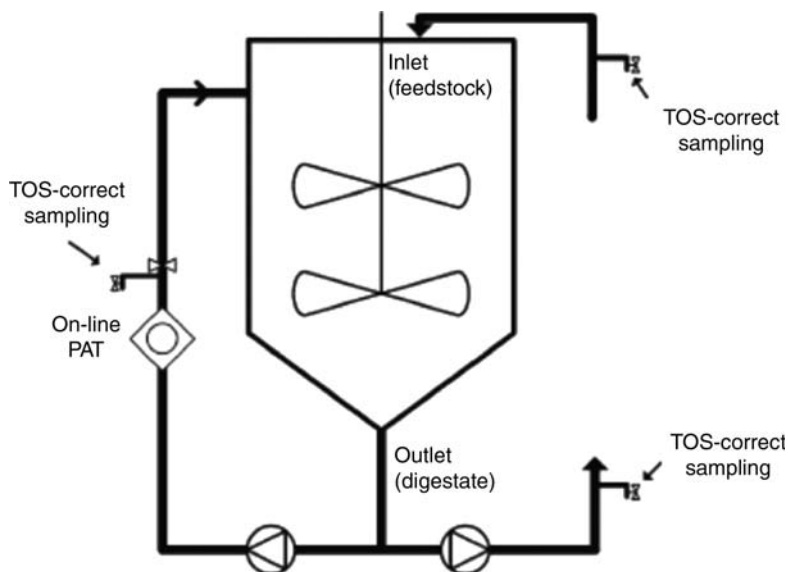
Fermentation processes at full scale are sensitive to sudden changes in feedstock composition that cause significant variability in the process conditions, i.e. organic overloading. Today, fermentation process control is usually achieved through manual sample extraction with off-line analysis of few key process parameters (Ahrling *et al.*, 1995; Nordberg *et al.*, 2000).

The time constants involved in AD do not have a critically short time response – from hours to days: the average hydraulic retention time of feedstock in a semi-continuous digestion system is of the order of 10 to 25 days and much longer in crop digestion (up to 100 days). However, organic overloading can often happen in a few hours and usually without knowing it is happening. Therefore, there is a need for implementation of inexpensive and robust on-line process monitoring technologies (Al Seadi, 2005; Hjort-Gregersen, 2005; Holm-Nielsen *et al.*, 2007). In order to obtain valuable results, correct sampling is needed, which has to be in accordance with the theory of sampling (TOS). This can be expressed as a TOS toolbox of unit operations to respect the principles of correct sampling under all kinds of harsh conditions in nature; good examples are any kind of sampling situations during fermentation processes of very heterogeneous bioslurry systems.

10.3.6 Sampling unit operations

In order to perform correct sampling in practice, always respecting the principles of the TOS, we only have to know about the following seven basic sampling unit operations (for more details see Petersen and Esbensen (2005)).

- *Structurally correct sampling* – the *only* safeguard against sampling bias.
- *Heterogeneity characterisation* of initial sampling material.
- *Homogenisation* – mixing, blending.
- *Composite sampling* – minimum of five composites per sample.



10.4 On-line PAT measurement and theory of sampling concept in a full-scale biogas fermentor or bioreactor setting (Holm-Nielsen, 2008).

- *Representative mass reduction* – so-called ‘riffle splitting’ or similar (more detailed info can be found in Petersen (2005)).
- *Particle size reduction* – grinding or crushing.
- *Lot dimensionality transformation* (3D or 2D → 1D or 0D) – transform three-dimensional and two-dimensional sampling places into optimal one-dimensional sampling places such as a pipeline (reactors or fermentors are 3D).

To overcome the difficulties in TOS-correct reactor sampling, a recurrent loop sampling concept can be introduced; this is essentially transforming the three-dimensional bioreactor sampling issue into a one-dimensional pipeline sampling situation (Fig. 10.4). To be fully representative, a vertical recurrent loop concept should be implemented. From such an external loop, pumping from the bottom of the reactor to the top, a full cross-section of the upward flow could be achieved as a composite sample by taking as many increments as necessary (Gy, 1998). Such a set-up would ensure an optimal ability to represent the entire volume of the fermentor. Structural correctness means that all parts of the sample material have an equal probability of being selected in the sampling procedure. This can obviously never be the case when samples are extracted from the side of a bioreactor (Petersen 2005; Petersen and Esbensen 2005; Mortensen and Bro, 2006).

Bioslurries in AD (and other fermentation processes) are almost always pumped in pipelines, fed in semi-continuously or continuously into the

bioreactor systems and, further on, to the post-treatment fermentation steps. On-line PAT measurements in pipeline systems at fermentation plants have huge importance and potential. This is especially important for heterogeneous slurries with a tendency to segregate. For bioslurries with a significant total solid content, this could easily lead to measurements with highly excessive sampling errors, if measured at-line in a static manner. A very important factor regarding the accuracy of measurement concerns the optimal analytical sample volume.

10.3.7 Multivariate data analysis: chemometrics as the final tool for PAT

Multivariate data analysis is the important third stage of the PAT triangle. Chemometric data analysis is explorative data analysis or, as described by the International Chemometric Society (ICS, 2006), ‘Chemometrics is the science of relating measurements made on a chemical system or process to the state of system via application of appropriate mathematical or statistical methods’.

Various methods of multivariate data analysis exist in chemometrics. These can be divided into three main types: (a) data description; (b) discrimination and classification; (c) regression and prediction (Esbensen, 2001). The main focus of biogas PAT studies is on multivariate regression and prediction of process parameters by processing near-infrared (NIR) spectra and other multivariate data from image analysis, electronic tongue or acoustic data sets of the heterogeneous bioslurry.

Chemometric data analysis gives an overview of the state of the chemical and/or biological processes based on analytical measurements. The idea of chemometrics is to let the process or the data structures unfold their relations themselves. From chemometric data analysis it is possible to decrease the required number of parameters (components) in order to describe the investigated phenomena, even though multivariate data analysis often starts with a much higher number of variables (Esbensen, 2001).

10.3.8 On-line AD monitoring possibilities

To summarise, process analytical technologies – including NIR, other light sources and acoustic (noise) sensor technology as PAT tools for on-line AD monitoring and process control – have produced better and better results in the past decade. Practical and commercial implementations are rapidly developing and on-line monitoring tools are receiving more and more attention from biogas plant operators (Holm-Nielsen, 2008; Jacobi *et al.*, 2011; Madsen *et al.*, 2011).

10.4 Mathematical process modelling and optimisation in practice

10.4.1 Mathematical modelling: a second option for process understanding and optimisation

Mathematical modelling of AD can also help control the process and avoid significant instabilities during fermentation. Such models can improve the understanding of biological processes. The correct evaluation and application of models has to follow particular stages in order to become an efficient tool. The main objectives of using a mathematical model are (Donoso-Bravo *et al.*, 2011)

- understanding the system's behaviour and the role of each particular component
- quantitatively verifying stated hypotheses
- predicting system behaviour in the future.

The model should also be balanced between describing the important characteristic of the systems and keeping a reasonable level of complexity (Nopens *et al.*, 2009). Several factors cause inhibition and failure of the process, for example overloading, underloading, inhibitory compounds, sudden temperature rise/drop, etc. (Mata-Álvarez *et al.*, 2000; Angelidaki, 2002). Hence, it is difficult to optimise the design and operation of the process in order to achieve the maximum performance. Pilot testing requires a long period of time and is costly, which is why application of mathematical models for predicting the performance of the process is of great interest (Parker, 2005). Models can be useful for understanding the numerous processes and microorganisms involved in AD. One needs to remember that a model first has to be calibrated but afterwards it should be able to predict reactor behaviour under changing conditions (Koch *et al.*, 2010). Over the years a range of models has been developed. The first attempts dealt with the steady state and assumed a rate-limiting step (Lawrence, 1971) but more complex models have since been presented (e.g. Lyberatos and Skiadas, 1999). The advantages of energy-based models are illustrated by Rodriguez *et al.* (2009) where the proposed modelling approach was based on a single metabolic network (as a representation of anaerobic microbial ecosystem) and on using a maximum-energy-yield selective force to define the reaction fluxes as a function of environmental factors.

10.4.2 Anaerobic digestion modelling developments and trends

The IWA Anaerobic Digestion Modelling Task Group constructed a generalised AD model (Batstone *et al.*, 2002) called ADM1 (previously discussed in Chapter 5). The group foresaw many benefits for the development of a generic model that could be related to practical or industrial applications, such as

- application for full-scale plant design, operation and optimisation
- process optimisation and control
- a common basis for model development and validation to make outcomes more comparable and compatible
- assistance for technology transfer from research to industry.

The ultimate goal was to support the increasing application of the AD process as a sustainable way to treat wastes and produce renewable energy (Batstone *et al.*, 2002). ADM1 includes disintegration, hydrolysis, acidogenesis and methanogenesis. In total, it accounts for 19 biochemical reactions associated with 7 bacterial populations. The kinetics is structured according to a Monod function of the substrate and takes into consideration pH, hydrogen and ammonia inhibition terms. Moreover, the model also accounts for physico-chemical reactions: liquid–gas transfer, acid–base reactions and pH (Batstone *et al.*, 2002). The model was tested in several different scenarios (Parker, 2005) where a number of data sets were examined. It is a very powerful tool when the feed stream is well characterised by COD content and the biodegradable fractions. Attempts for validation against pilot plant experiments (Blumensaat and Keller, 2005) were also carried out. Blumensaat and Keller (2005) stated that several updates had to be implemented to fit the existing models to pilot-scale performances. Another example of the model extension was presented by Fezzani and Cheikh (2009) who attempted to include the degradation of phenols. Concerning mono-digestion systems, Koch *et al.* (2010) and Thamsiriroj and Murphy (2011) modelled grass silage digestion and both groups found good agreement of the model with measured data. The first study was focused on a description of nitrogen incorporation and release to predict the nitrogen ammonia curve, whereas the second study aimed for recommendation of the process configuration and the level of liquor recirculation. Mairet *et al.* (2011), on the other hand, performed work on modelling the anaerobic digestion of microalgae, one of the new promising sustainable raw materials for biofuels production. A dynamic model of microalgae-based AD could help understand the complexity of the process and identify possible optimal solutions.

Different models have addressed a number of aspects crucial for

describing the behaviour of process reactions and have been reported to successfully predict digester operation, failure and remedies (Lyberatos and Skiadas, 1999; Batstone *et al.*, 2006). Proper modelling ought to take into consideration both biochemical and physico-chemical reactions. The effect of pH, temperature and gas-liquid phase mass transfer also must not be ignored. The effect of inhibitors such as oxygen, chloroform, halogenated organics, heavy metals, etc. should also be studied.

10.4.3 AD mathematical modelling: current status and perspectives

Astals *et al.* (2011) stated that ‘the power of the models lies in their capacity to reproduce an empirical behaviour in a computer in a clear and quantifiable manner, where the mathematical equations are able to simulate the physical, chemical and biological processes’. One of the challenges in the recent development of mathematical models is the capacity of the system to simulate the AD process where two or more substrates are applied. One of the key issues would be to predict the nutrient limitations for the process (Astals *et al.*, 2011). Gali *et al.* (2009) developed an ADM1-based model suitable for anaerobic co-digestion of agricultural wastes. The work was further extended by Astals *et al.* (2011) who accurately predicted the degradation of pig manure and glycerine. Other examples of the implementation of mathematical models for AD are given by, for example, Rosen *et al.* (2006) and Nopens *et al.* (2009).

The information presented on mathematical modelling of the AD process is not intended to give a full review of the existing literature. Given the large number of scientific publications existing and new ones being constantly published, it couldn't be – it is rather about underlining the idea of how important, useful and powerful mathematical modelling is in process design, operation, optimisation and, consequently, control.

10.5 Advantages and limitations of process control

The advantages of integrating process control in anaerobic digestion sectors are multiple. Monitoring, managing and controlling AD in the future is a must. The AD industries are becoming more and more mature and advanced over time. In the near future, biogas production will play an important role in an overall energy share and it will take over the position from natural gas. All of this means that a constant and controllable flow of biogas will have to be supplied to society.

As in other advanced fermentation industries, there is a great need for optimised, on-line process control for the AD process. The AD sector is

complex, converting a variety of input materials into useful biomethane. Because the biogas process will play such an important role in the future, it has to become better controlled. Experience learned from AD can then be spread to other renewable energy or biorefinery facilities. The control of high complexity feedstocks and process steps is definitely a challenge, but at the same time it stimulates the research community. Process parameters and control possibilities are becoming more and more mature all the time.

The problems of many studies concerning AD process control are that they are often limited to a few indicators. In a highly complex biological process such as AD, this might send a false message. Moreover, most of the techniques still require quite intensive and expensive analytical work. Many of the new on-line monitoring systems first have to be carefully calibrated and then can only work in very specific conditions. In AD processes, where the feedstock is very heterogeneous and can change during the year (unless it is a mono-digestion process), this creates certain challenges. Building a flexible, stable and low-cost process control system is a difficult task, but is certainly obtainable.

10.6 Conclusion and future trends

Process control and monitoring are important strategies for achieving higher efficiency in the anaerobic digestion process. In order to have proper process control, continuous or semi-continuous process monitoring is necessary. One should not forget the challenging issue of correct sampling, especially in such a heterogeneous environment as anaerobic digestion. More and more technologies and new strategies are becoming available to support biogas production. The future trend is to maximise simplification of the required procedures and make available on-line monitoring with early warning strategies to help avoid significant process disturbance. The aim is to move the process efficiently towards its theoretical maximum, improve and stabilise biogas economy and avoid the risk of financial failure of biogas projects.

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Methane emissions in biogas production

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Abstract: Biogas is produced by anaerobic digestion of manure, energy crops (mainly maize), wastewater treatment sludge and organic waste. Biogas is a renewable energy source. Sustainability requirements are increasingly important. As a greenhouse gas, methane is 25 times stronger than carbon dioxide, so small leakages of biogas have a strong negative effect on the total greenhouse gas performance of the energy production pathway. This chapter covers an overview from the literature concerning methane emissions from different steps in the biogas production chain with reference to relevant selected articles.

Key words: greenhouse gas, methane, emissions, sustainability, literature search, biogas, green gas.

11.1 Introduction

A total of 16.5 billion Nm³ biogas, equal to 8.3 MTOE (million tonnes of oil equivalent) biogas (97 TWh), was produced in Europe in 2009.¹ This biogas is produced by anaerobic digestion (AD) of manure, energy crops (mainly maize), wastewater treatment sludge and organic waste. Most of the biogas is fed to co-generation sets, consisting of an engine-generator system that converts the biogas to renewable electricity and heat. An increasing proportion of the biogas is upgraded to natural gas quality and fed to natural gas grids or is used as transport fuel.

Biogas is a renewable energy source. Sustainability requirements are

¹ Source: <http://www.eurobserv-er.org>. 8.3 million tonnes oil equivalent biogas equals 16.5 billion Nm³ biogas, based on 41.868 GJ per ton oil and 21 MJ/Nm³ biogas.

increasingly important. One of the requirements is the greenhouse gas performance of the energy production pathway. For AD, three greenhouse gases are important in this: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Since biogas contains about 60% methane, this gas is especially important in biogas production pathways. As a greenhouse gas, methane is 25 times stronger than carbon dioxide,² so small leakages of biogas have a strong negative effect on the total greenhouse gas performance of the energy production pathway.

To date, there have been only a small number of detailed studies on methane emissions from biogas production, distribution and utilization. In this chapter, the results of these studies are summarized, their main conclusions are assessed and gaps in the knowledge in this field are identified.

11.2 Methane emissions in biogas production

In the open literature there are about ten key articles dedicated to emissions from biogas production and biogas utilization, and a few additional publications that address particular aspects of biogas production. In this chapter, an overview of the production process is given first, indicating the key steps with regard to emissions. Then each process step, as shown in Fig. 11.1, is described in detail.

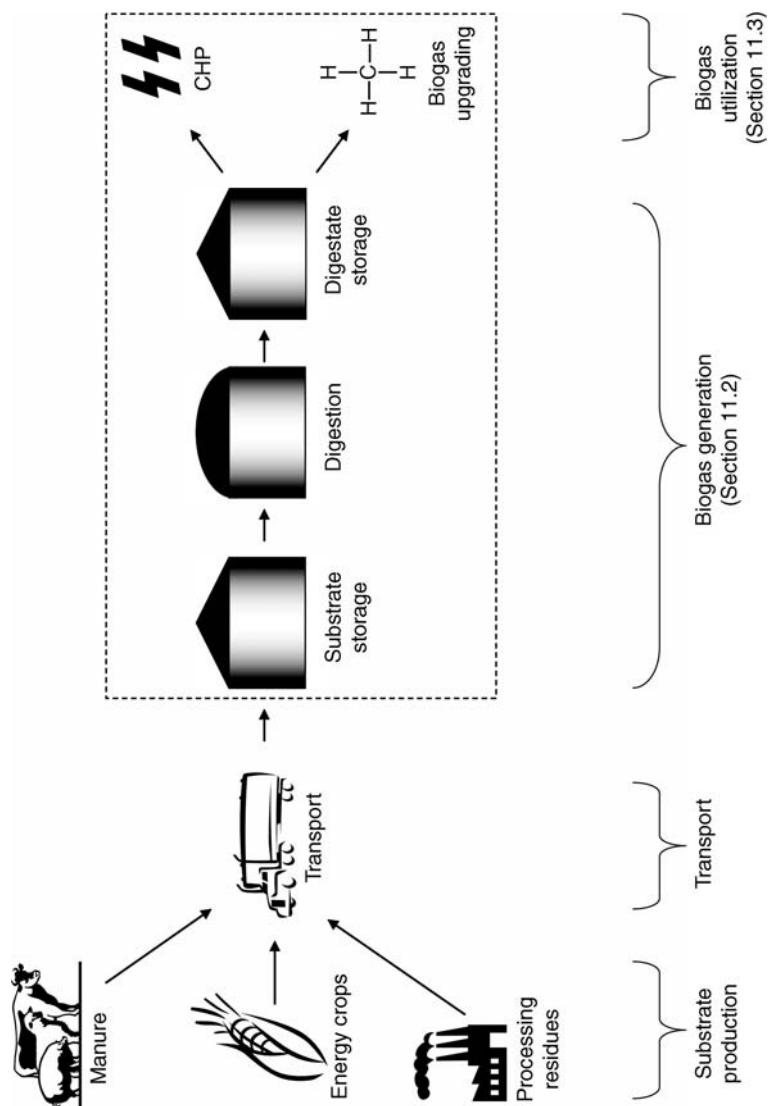
The scope of this chapter covers methane emissions from the production of biogas and the utilization of the biogas in processes that are typically carried out at the same site as the biogas production. Therefore, the following processes are excluded:

- emissions from the production of energy crops
- emissions from animal stables and manure storage at farms
- emissions from industrial processing facilities in cases where an emission could be allocated to the co-product
- emissions during transport of substrates
- emissions from the gas grid or gas stations after injection into the grid.

Numbers are presented as they are given in the literature so it is possible to refer back to the original articles. In addition, all emissions are also expressed as a percentage of the total methane that is utilized, to allow comparison between steps.

In the interpretation of the results from the storage of manure and

² The global warming potential of methane is 25, compared to 1 for carbon dioxide. This is mass-based and for a 100-year time horizon. In recent years, three values have been used: 21 (IPPC Second Assessment Report, 1995); 23 (IPPC Third Assessment Report, 2001); 25 (IPPC Fourth Assessment Report, 2007).



11.1 Steps in the biogas production pathway (dotted line represents the system boundary for the purposes of this chapter).

Table 11.1 Net total methane emissions during storage and after field application of differently treated manure (in gCH₄/m³ manure)

	Untreated	Separated	Digested	Straw cover	Aerated
Storage	4045.7	1833.0	1242.6	4904.1	1731.7
Field application	1.3	19.7	2.0	22.2	7.6
Total emissions	4047.0	2363.3	1344.6	4926.3	1739.3
Storage (%)	100	99.2	99.9	99.6	99.6
Application (%)	0.0	0.8	0.1	0.4	0.4

digestate, it is important to realize that long-term storage only takes place with either manure or digestate, never with both. The latter would result in an overestimation of the emissions. Finally, it is important to realize that although emissions from long-term storage of manure are discussed briefly, this aspect is outside the scope of the current chapter.

11.2.1 Storage of manure and substrates

Two articles report on emissions from the storage of manure or substrate. In the first of these, Amon *et al.* (2006) sought to quantify methane emissions, along with ammonia (NH₃) and nitrous oxide emissions, from storage and after application of differently treated dairy cattle slurry (pure manure). The treatment options were AD, slurry separation, slurry aeration and straw cover, and their influence on emission levels was investigated. The main focus was to compare net total emissions from manure storage and after manure application. The results are presented in Table 11.1.

The net total methane emissions during storage of untreated cattle manure were found to be 4045.7 gCH₄/m³ manure in an open manure storage. No emission numbers were reported as a percentage of total methane utilization. Assuming cattle manure with a density of 1 ton/m³ and a biogas yield of 21 m³/ton, the reported emission of 4045.7 gCH₄/m³ yields 192.7 gCH₄/m³ biogas. With an average methane content of 60% and methane density of 710 g/m³, this corresponds to 45% of the total methane produced. Note that this result was based on net total emissions from long-term (80 days) slurry storage under warm conditions with a mean slurry temperature of 17°C.

Overall, methane emissions from stored dairy cattle manure were reduced by all treatments except when the manure store was covered with a layer of chopped straw. Greenhouse gas abatement measures for the management of stored manure were most effective if they reduced methane emissions during slurry storage. In the context of manure destined for AD, this can best be achieved by a reduction in slurry dry matter.

In the second study, a report commissioned by the Dutch government (SenterNovem, now the NL Agency), Zwart *et al.* (2006) reported methane

Table 11.2 Reported emissions from different AD components

AD components	Configuration	Min. average loss of methane (%)	Max. average loss of methane (%)
Silage storage	—	0.00065	0.00065
Feeding systems	Screw conveyor	0.0079	0.0079
	Dosing feeder	0.00029	0.16
	Substrate storage tank	0.005	0.311
	Mixing tank	0.013	0.288
Digester	Foil cover	0.006	0.0244
	Gas-tight cover	0	0
	Concrete roof	0	0
Digestate storage tank	Open	0.224	11.22
	Covered	0.638	10.299
Gas utilization	CHP	0.44	2.43
	Upgrading	1.5	1.5

emissions of 1800 gCH₄/ton manure for manure storage. With the same assumptions as above, this corresponds to 20% of the total methane produced. It is noted that the long-term storage of 80 days refers to storage at farms and actually is outside the scope of this study. However, this is included here to give some insight into the magnitude of storage emissions. A typical storage period at a digestion plant is around one week, and corresponding emissions will therefore be around 10% of the values mentioned above.

Liebetrau *et al.* (2011a, 2011b) analyzed emissions from ten biogas plants with different types of components, capacity, process conditions and so on. The study focused on five major plant components: silage storage, feeding systems, digester (foil cover, gas-tight cover), digestate storage tanks (sealed, not gas-tight covered and open) and gas utilization (CHP or upgrading). The average methane emissions are summarized in Table 11.2.

Focusing on emissions during silage storage, the average loss of methane at the ten biogas plants was shown to be extremely low, amounting to only 0.00065% of methane produced. This is considerably lower than the value reported by Zwart *et al.* (2006), who mentioned that methane emissions during long-term storage of substrate are 3100 gCH₄/ton substrate. This depends not only on the biogas yield of the energy crops, but also on process conditions such as the storage temperature and storage period. Since the data of Liebetrau *et al.* are based on actual measurements while those of Zwart *et al.* are based on an assumption that could be invalid, it can be safely concluded that emissions from storage of co-substrates are negligible.

Zwart *et al.* (2006) also note that 95% of methane emissions during

manure storage can be avoided by feeding the manure as soon as possible to the digester. This is not the case for stored co-substrates.

In this chapter, emissions have been converted to a percentage of the methane that is actually utilized. These relative emissions from storage of substrates, however, depend on the feedstock mix that is applied at the AD plant. For manure, methane emissions from storage are significant, but potential biogas production is low, leading to high relative emissions. For other co-substrates, the opposite is true. Since the specific biogas production from co-substrates is generally much higher than for manure, the relative emissions from the combined feedstock are much lower than for manure alone.

This can be explained by assuming a feedstock mixture of 50% manure and 50% maize. The emissions from the short-term storage of the manure will be 10% of $1800\text{--}4000\text{ gCH}_4/\text{m}^3$ manure, with a biogas production of $21\text{ m}^3/\text{m}^3$ manure. Emissions from the storage of maize are negligible, but biogas production is $180\text{ m}^3/\text{ton}$. The combined emission is $180\text{--}400\text{ gCH}_4$ for 201 m^3 of biogas produced. With 60% CH_4 in the biogas, this corresponds to an emission of 0.2–0.5% of the methane production. For a feedstock mix with 50% manure and 50% maize, the relative emissions from feedstock storage can be estimated at 0.2–0.5% of methane available for utilization.

11.2.2 Digester

In the analysis of greenhouse gas emissions from ten biogas plants within the agricultural sector, Liebetrau *et al.* (2011a, 2011b) reported on emissions from digesters with different types of covers. Besides the detected leakages, the general emissions from the digesters with supposedly gas-tight covers were quite low. Leakages generally resulted from poorly maintained service and inspection ports and a poor design and/or quality of lead-through pipe work. No emissions were detected after taking care of these types of leakages. Digesters with a concrete roof did not show detectable emissions at all. For digesters with a flexible foil cover, emissions were occasionally reported. The maximum emissions amounted to 0.0244% of the utilized methane. All emission sources were traced to the connection between the foil and the digester. No emissions were found through the membrane material itself.

In a report commissioned by the Swiss Bundesamt für Energie (BFE), Büeler (2011a, 2011b) reported experimental data for emissions due to diffusion or leakage through membranes fixed on top of a digester. This work dealt specifically with possible emissions from the gas buffers commonly applied in biogas plants, consisting of a flexible ethylene propylene diene monomer M-class rubber (EPDM) membrane, normally fixed to the top of the digester; such gas buffers are applied either as a single- or double-membrane version. In the single-membrane version, the volume

of the buffer varies due to expansion of the membrane itself. The shape is typically that of a sphere. In the double-membrane version, the inner membrane is protected from weather influences by an outer membrane. The space in between the membranes is flexible and is ventilated with ambient air. Instead of EPDM, polyethylene is used as membrane material in these buffers. In both cases, any diffusion or leakage through the inner membrane will lead to emission of methane.

Büeler investigated the magnitude of the permeation through the membrane under clearly defined laboratory conditions. The potential influences of a number of circumstances were determined, as follows.

- Thickness of the membrane. Applied membranes vary in thickness between 0.8 and 2 mm, generally being around 1.5 mm; the thickness was found to be inversely proportional to the permeation rate.
- Effect of aging. No clear dependence between age and diffusion rate could be established.
- Effect of organic acids in the fermenter. An indication of increasing permeation with increasing acid concentrations was shown, but this was not considered statistically significant.
- Effect of substrates treated in the digester. No influence of variations in substrates was determined.
- Influence of expansion of the membrane. Expanding the membrane by 40% of its original dimensions increased the permeation by 23–24%. This is a result of the decrease in thickness connected with the expansion.

The actual emissions for biogas plants were estimated based on the permeation rate, the degree of expansion of the membrane and the dimensions and gas production at ten different biogas plants. The conclusion drawn for single-membrane gas buffers made from EPDM was that the methane emission by permeation through the membrane was 0.26% of the average volume present in the biogas buffer. For double-membrane buffers, where polyethylene was applied instead of EPDM, the permeability of the polyethylene was stated to be only 10% of the value for EPDM.

It is also important to note that the figure of 0.26% refers to the average volume in the buffer. Generally, biogas buffers are designed to hold a capacity equal to a number of hours of biogas production (4–6 hours). This means that the biogas volume that passes through the buffer is 4–6 times larger than the volume of the buffer itself. In relation to biogas production, the methane emission would only be 0.040–0.065% (earlier literature mentions a value of 0.1% of the methane production).

Thus, the overall conclusion of this particular study was that methane emission by permeation through the EPDM membrane was between 0.040 and 0.065% of total biogas production. Where polyethylene membranes are

Table 11.3 Results of methane slip measurements in gas engines

Source	Electric power (We)	CH ₄ concentration in biogas (mg/Nm ³)	CH ₄ concentration in flue gas (mg/Nm ³)	Remarks
Germany	30–340	55	290	Refers to C _n H _m emissions, which are approximately equivalent to the CH ₄ concentration for combustion of biogas
Denmark	—	65	880–920	2200–2300 for natural gas with a conversion factor for biogas of 0.4
Austria	348	64	861	
(4 different biogas	249	61	2333	
–CHP plants)	130	60	280	
Laaber <i>et al.</i> (2007)	500	55	1100	The value stated was 1.79% of the CH ₄ input (assumption of 5% oxygen concentration in the CHP flue gas)

employed, emissions are much lower because their permeability is only 10% of the permeability of EPDM membranes. In newer plants, the application of double membranes is considered to be ‘state of the art’.

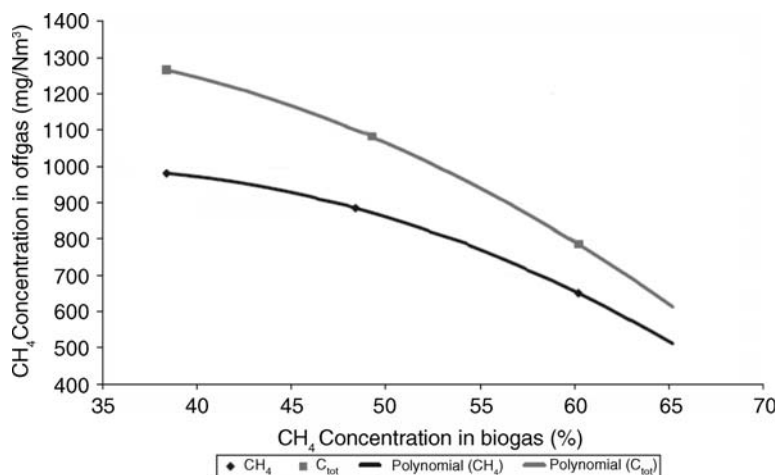
11.3 Methane emissions in biogas utilization, biogas upgrading and digestate storage

11.3.1 Biogas utilization and upgrading

Combined heat and power

Liebetrau *et al.* (2011a, 2011b) concluded that biogas utilization in a gas engine was the second major source of methane emissions. Methane slip measurements for eight combined heat and power (CHP) systems with different capacities showed emissions ranging from 0.44 to 2.43% of the utilized methane.

Work by Woess-Gallasch *et al.* (2007a, 2007b) gives an overview of results provided in the literature for emissions as a result of methane slip in CHP engines, together with results of methane concentration measurements in flue gases of biogas-powered CHP plants in Austria, Denmark and Germany (see Table 11.3). The measured values are between 280 and



11.2 Methane emissions from a pilot CHP injection as a function of the methane potential.

2333 mg/Nm³. Going by these results, a methane slip value of 1.79% could be considered as representative, since the resulting methane concentration of 1100 mg/Nm³ lies in the middle of the spectrum of the presented values, which agrees with the results reported by Liebetrau *et al.* (2011a, 2011b).

Laaber *et al.* (2007) report that, in biogas CHP, the methane concentration decreases with increasing methane content in the biogas. The relationship is shown in Fig. 11.2. Laaber *et al.* (2007) confirmed the result of methane emissions from biogas CHP. The methane slip of a 500 kWe CHP with an average concentration of about 55% methane in clean biogas was 1.79% of the total annual amount of methane.

In a study and follow-ups commissioned by the Dutch government, KEMA reported the results of measurement programs (Oltuis and Engelen, 2007; Engelen, 2009; Oltuis, 2010) on methane emissions from natural-gas-fueled gas engines. The studies revealed many measurement uncertainties, which were attributed to sampling errors and errors related to measurement methods such as exhaust gas conditioning, accuracy of calibration gases and specifications of the analysis equipment employed. The methane emissions ranged from 0.6 to 3.0% of the fuel input. A further study from the Netherlands by de Zwart *et al.* (2011) referred to the KEMA measurements and the uncertainties revealed, and reported on methane emissions from gas engines in CHPs at horticulture companies in the Netherlands. The article was not based on new measurements, but explained what and how process parameters can influence the methane slip.

Finally, a Danish study by Kristensen *et al.* (date of report unknown) reported on gas engines between 1992 and 1998, based on around 500 field

measurements of natural gas engines and 14 biogas engines. They found a range for the methane emission of 1–6% of fuel input. However, this was based on relatively old engines that have most likely been replaced by now. An interesting conclusion was that the methane emission was 40% lower for the biogas engines compared to the natural gas engines. The authors of this chapter believe that methane emission differences between biogas engines and natural gas engines are not necessarily characteristic and cannot simply be explained by differences in methane content. The difference can be explained by the fact that the methane number of biogas is around 130, allowing for high compression ratios and early spark timing. Also, the capacity of the engines and the number of measurements will both influence the final results (see also Chapter 17 on CHP for further information).

Biogas upgrading

The previously mentioned work of Liebetrau *et al.* (2011a, 2011b) is the only study among the original set of articles to report specifically on methane emissions during gas utilization. Two of the ten biogas plants investigated by Liebetrau *et al.* had a gas upgrading facility with pressurized water scrubbing. From the two gas upgrading units, only the results of one of them were presented. The reported emission of methane during the regeneration part of the process was 1.5% of total methane production. In Germany, from 2012 onwards, the maximum allowable methane slip in upgrading installations is 0.2%.³

In recent years, two biogas upgrading installations in the Netherlands (Beverwijk and Mijdrecht) have been monitored and the results are reported by Jonker (2010a, 2010b). For Beverwijk it was found that no methane slip occurred. This is a direct result of the thermal treatment (combustion) applied to the residual gas at the plant. This approach was chosen because of the relatively high methane concentrations in this residual gas. Despite the low efficiency of methane production at the Beverwijk plant, the effectiveness of the combustion treatment process demonstrates very well that essentially zero methane emissions can be achieved in practice.

In Mijdrecht, a state-of-the-art upgrading plant using a chemical washing liquid is applied to remove carbon dioxide. This process is highly selective and the residual gas from the regeneration of the washing liquid contains only small amounts of methane. The methane slip that was derived from the measurements was 0.2% of the input. The result from this plant indicates that the future German requirements can be met with the application of appropriate technology.

³ According to the Gasnetzzugangsverordnung (GasNZV) (<http://www.biogaspartner.de/index.php?id=10141>).

Boilers and flares

No experimental data have been reported regarding boilers and flares in the literature covered in this chapter.

11.3.2 Storage of digestate

Methane emissions during digestate storage are considered by Amon *et al.* (2006), Woess-Gallasch *et al.* (2007a) and Liebetrau *et al.* (2011a, 2011b). Among the different treatment options, AD of manure is reported to lead to the highest methane reduction. Amon *et al.* (2006) report that 1242.6 g of methane are emitted per m³ of digested cattle manure. This corresponds to 14% of the total methane production.

In a report commissioned by the LandesEnergieVerein Steiermark in Graz, Austria, Woess-Gallasch *et al.* (2007a) investigated possible emissions of methane and other greenhouse gases from biogas plants. Specific measurements were performed for the emissions from the digestate buffer of a full-scale biogas plant in Paldau, Austria. Greenhouse gas emissions from other sources were estimated on the basis of literature values and applied in a life cycle assessment for different configurations.

The digestate buffer at the plant investigated had a closed container with a concrete roof. The feedstock for the previous digestion step was a combination of cattle and pig manure along with corn and grass silage. The biogas production in this buffer and the actual methane concentration were measured and considered to be representative for a similar plant with an open digestate buffer. The production of biogas resulted from continuation of the digestion process in the buffer, as the temperatures remained near the optimal digestion temperature. Emissions in the summer months (between May and October 2006) were determined, corresponding to a complete cycle of filling up and withdrawal.

The total biogas production of the plant was 2365 million Nm³ of biogas, corresponding to an input of 9.900 tons of feedstock. The feedstock comprised corn silage (27%), corn cobs (32%) grass silage (7%), pig manure (31%) and cattle manure (3%). The plant consisted of two main digesters and two secondary digesters, with residence times of 64 and 35 days respectively. These values were considered representative.

The yearly biogas production corresponded to 270 Nm³/ha on average. The emission from the digestate buffer was determined to be 3.9 Nm³/ha. The methane content in the biogas was 63.8% and was clearly higher than the average methane content of the biogas produced, which was 48.8%. Taking this difference into account, the methane loss from the digestate buffer was determined as 1.9% of the total production of methane.

It should be noted that this calculation was based on the assumption that

the closed buffer in the investigation was representative of an open buffer. In practice, an open buffer would show a higher heat loss and therefore lower average temperatures than for the situation under investigation. This would likely reduce the production of methane in the digestate buffer. The value presented was therefore a conservative value. It should also be mentioned that the methane emissions from open storage systems depend on the hydraulic retention time of the material in the digesters.

The above-mentioned result is representative for plants with long digester retention times (longer than 100 days). In plants with the same feedstock and a shorter retention time, the methane emissions during the digestate storage phase would be higher, as less of the biomass carbon content would have been converted to methane during the digestion stage.

The results presented by Liebetrau *et al.* (2011a, 2011b) on open digestate tanks are not consistent because the emissions depend on many process parameters (temperature, retention time, pressure, wind velocity, filling level and so on). Results from ten digestate tanks show that some of the storage tanks can produce substantial emissions, whereas others show very little by way of emissions. Two types of digestate storage tanks were investigated – open and covered. Methane emissions for open tanks ranged between 0.224 and 11.220% of the utilized methane. For covered tanks, methane production (not emissions) amounted to 0.638–10.299% of the utilized methane. The authors of this chapter believe that the similarity between methane *produced* in a covered storage tank and methane *emitted* from an open storage tank can be explained by coincidental occurrence and is not directly connected to the process parameters mentioned above. Emissions from properly covered tanks can be avoided to the same extent as in the digester and for manure storage.

In the study by Amon *et al.* (2006), the lowest methane emissions were measured from anaerobically digested slurry, as the fermentation process in the digester had already degraded a considerable part of the organic dry matter to methane and carbon dioxide. However, methane formation continued during storage of the digested substrate. Methane produced after the substrate has left the digester should be collected as well and used as energy source.

Liebetrau *et al.* found the main emission sources to be the open digestate tanks and the gas utilization system. The results for the open digestate tanks do not represent the average emissions because they depend on too many influencing factors (e.g. temperature, retention time, weather conditions, etc.) and therefore can only represent a very short time span. All other components play a minor role as long as they function properly and have no leakages.

Burgstaler *et al.* (2011) reported losses up to 7% after a storage period of one month. This storage period is shorter than the storage periods

maintained in the study of Liebetrau *et al.*, which also explains the difference in maximum emission numbers (i.e. 7% as opposed to 11%). In greater depth, their report discusses the potential of addition of sodium bicarbonate (NaHCO_3) to digesters in order to stabilize the process conditions and optimize the conversion of organic material. By improving the conversion it is expected that the residual gas potential in the digestate will decrease.

Tests were performed with three laboratory-scale digesters (10.4 l), that were given the same feed on a continuous basis (daily feed). One reactor served as the control, while the other two were treated with different doses of sodium bicarbonate. In order to demonstrate the stabilizing effect of the addition, the reactors were subjected to a relatively high loading of organic material (up to 6.5 kg/m^3 per day; generally, a value of 4 kg/m^3 per day is applied). The tests showed that the residual biogas production in the three weeks following active digestion was between 5.6% and 6.7% of the captured biogas quantity during active digestion. This is an indication of the amount of biogas that could be released in an open storage of digestate.

The results for the remaining gas potential have to be regarded as an upper limit based on the following considerations.

- The reactors were deliberately loaded to stressful conditions, where conversion of organic matter is not optimal.
- The applied loading rates were around 1.5 times as high as in normal practice.
- The conversion rates achieved were considerably lower than those normally found in practice, with a methane production of $123 \text{ Nm}^3/\text{kg OS}_{\text{input}}$ versus practical averages of around $370 \text{ Nm}^3/\text{kg OS}_{\text{input}}$.

Mainly because of this last result, the representativeness of the reported data for the practical situation of operational digesters appears to be limited.

11.4 Overall methane emissions

In a peer-reviewed paper, Flesch *et al.* (2011) report the results of measurements on overall methane emissions from a Canadian 1 MW biogas plant (a 100 ton/day co-digestion plant). The installation consisted of feedstock hopper, gas-tight digester (with rubber cover), digestate separator, digestate liquid lagoon, digestate solid fertilizer output tent, CHP, flare and the piping around this equipment. The smaller 'secondary' emissions from other sources outside this area (feedstock piles, runoff ponds and the offal storage area) were estimated.

An inverse dispersion technique was used to measure the totality of emissions. This is a micrometeorological method that uses a downwind concentration measurement to calculate the gas emission rate. Emissions

Table 11.4 Fugitive emissions as a percentage of seasonal biogas production rates

	Autumn	Winter ^a	Spring ^b	Summer ^c	Average
Normal (%)	2.9	2.7	5.2	1.7	3.1
Flaring (%)	20	25	—	13	19
Maintenance (%)	0.5	—	1.8	—	1.2

^a No maintenance during winter measurements.

^b No flaring during the spring measurement; also low biogas production due to non-ideal feedstock material.

^c No maintenance during summer measurements.

were measured during autumn, winter, spring and summer seasonal campaigns, with each campaign lasting 6–7 days. Three operation periods were identified – high emissions during biogas flaring low emissions during plant maintenance and emissions during normal operation. The seasonal fugitive emissions as a percentage of methane production rates are shown in Table 11.4. The results show that during normal operations, the emissions ranged from 1.7% in the summer to 5.2% in the spring. Over all four seasons, the average was 3.1% of gas production. The emission rate over any prolonged period will ultimately depend on the frequency of flaring and maintenance. During normal operations, the feedstock hopper was identified as the main source of emissions.

In a report for Avfall Sverige (a Swedish waste management company), Rylander and Wqvist (2007a, 2007b) elaborate on how to measure emissions in biogas plants, but do not include any measured result. The report is based on Swedish installations. The authors describe the voluntary agreement for biogas plants, introduced in 2007 by Avfall Sverige, whereby the owners of biogas plant commit themselves to identify and reduce their emissions systematically. Their report explains how the system is built, including a systematic method for leak detection and emission measurements, reporting and methods for reducing emissions. The system boundary is defined as only those items owned by the owner of the plant and the items that the owner may influence. Therefore, items related to the compression of biogas, propane dosing for injection into the net, gas storage and filling stations fall outside the system boundary. In addition, the system covers only the parts that are related to the production, purification and upgrading of biogas. Emissions associated with the use of gas (CHP), manure and digestate and the emissions associated with transport of substrates, fertilizers and gas are not included in the system. Of the greenhouse gases in a biogas system, only methane is considered to be in the system.

The most critical points in a biogas plant are the parts that are not coupled to the gas system of the plant, but still may have emissions of methane. According to Rylander and Wqvist, the main emission points in a

Table 11.5 Data availability in all articles (see Section 11.6)

Reference	Storage substrates	Digestion	CHP	Upgrading	Storage digestate	Overall plant
Flesch <i>et al.</i> (2011)						x
Liebetrau <i>et al.</i> (2011b)	x	x	x	x	x	
Liebetrau <i>et al.</i> (2011a)	x	x	x	x	x	
Amon <i>et al.</i> (2006)	x				x	
Rylander and Wiquist (2007a)						
Rylander and Wiquist (2007b)						
Vonk and Verbeek (2010)						
Woess-Gallasch <i>et al.</i> (2007a)			x		x	
Woess- Gallasch <i>et al.</i> (2007b)			x		x	
Büeler (2011a)		x				
Büeler (2011b)		x				
Frantz (2011)						
Oltuis and Engelen (2007)			x			
Engelen (2009)			x			
Oltuis (2010)			x			
de Zwart (2011)			x			
Kristensen <i>et al.</i> (undated)			x			
Zwart <i>et al.</i> (2006)	x				x	
Burgstaler <i>et al.</i> (2011)					x	

biogas plant are the ventilation systems, mixing tank, main digester tank, second digester tank, dewatering and digestate storage. The main source of emissions in a biogas upgrade installation is the point where the residual gas is released into the atmosphere through air or outflowing washing water.

11.4.1 Literature coverage

As has become clear in the previous sections, most available articles cover only a part of biogas production. Table 11.5 gives an overview of the data available in these sources.

11.5 Conclusion and future trends

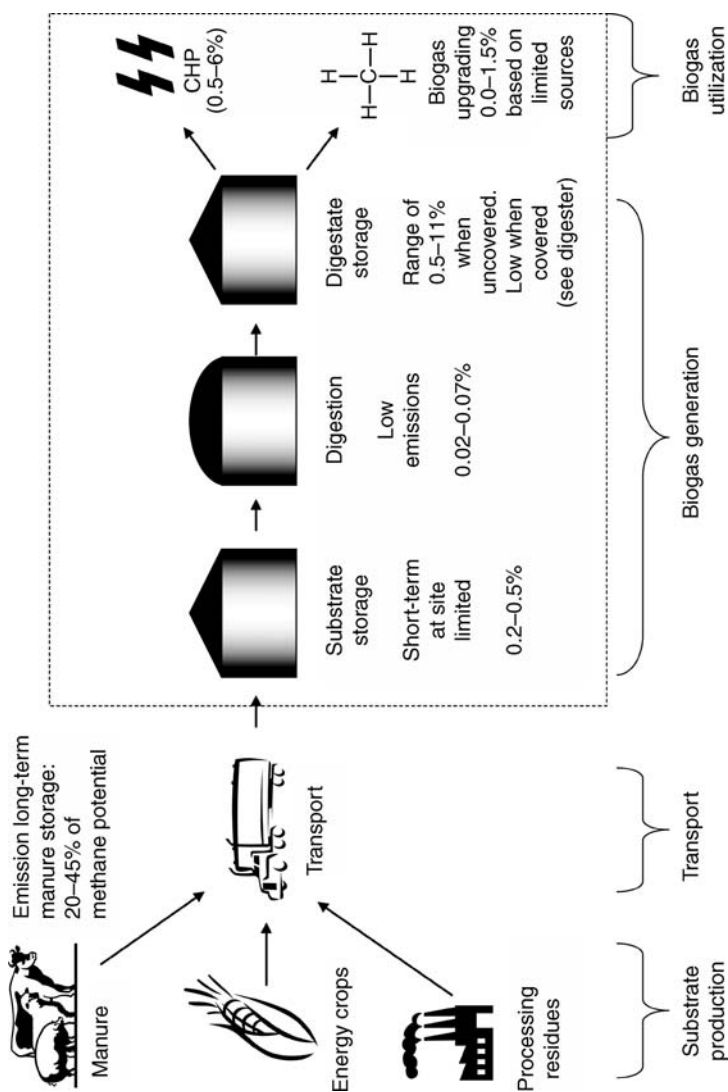
- *Scope.* A number of recent articles and presentations on methane emissions from biogas production have been reviewed. This chapter focuses only on biogas production and utilization of the biogas until the

points where the biogas is supplied to a grid either as upgraded biogas (green gas) or as electricity and heat. Storage of the digestate is included. Excluded are emissions from the production and transport of (co) substrates and the distribution and final use of upgraded biogas.

- *Results.* Figure 11.3 summarizes the emission results in different biogas production chains.
- *Emission from storage of substrates.* The storage of manure is one of the most important sources of methane emissions. Based on two sources, a range of 20–45% of the total methane production has been found. This is a large range, but it is clear that (long-term) storage of manure results in very significant methane emissions. It should be noted that emissions from storage also take place when the manure is stored for uses other than biogas production. In fact, in combination with digestion, long-term storage of manure is not practised as this has a negative impact on gas potential. Instead of manure, the digestate is the main product that will be stored over long periods, when land application is not allowed (e.g. in winter).

Although the reported numbers vary significantly, it can be concluded that emissions from the storage of co-substrates, such as silage of various agricultural residues, are negligible. Taking a mix of feedstocks into account (manure and co-substrates), the (short-term) substrate storage at a biogas plant results in a relative emission of 0.2–0.5% of methane production.

- *Emissions from digestion.* Two articles discuss emissions from digesters. Besides leakages resulting from poor maintenance, both articles report limited emissions, from 0.02 to 0.07% of the total methane production for foil-covered digesters.
- *Emissions from gas engines.* Many of the studies report on emissions from natural-gas-fueled engines. It is not clear from the studies to what extent this represents the emissions of biogas-fueled engines, although there is no reason to assume this differs very much. The reported methane slip shows a wide range, from 0.5% up to 6.0%. The authors of this chapter conclude that this is one of the most important sources of methane emissions.
- *Emissions from biogas upgrading.* Very few quantitative data are reported on methane losses in biogas upgrading. Equipment suppliers give numbers relating to leakage, but limited independent measurements are available. The sources based on measurement reports indicate methane emissions up to 1.5% of the total methane production. From the experience of the present authors, the market for biogas upgrading technology is still developing and none of the available upgrading technologies has yet become dominant. Since the leakage of methane



11.3 Summary of results (emission percentages based on total methane utilized).

depends on the upgrading technology, numbers for each of the technologies should be measured.

- *Emissions from digestate storage.* A wide range of emissions from digestate storage tanks has been reported: roughly from 0.5 to 11.0% of the total methane production in one study and around 7% in another study. Some of the results came from measurements using closed tanks. The captured production in these closed tanks is considered representative of emissions from storage in open tanks.
- *Overall emissions.* Considering the above-mentioned sources, including the uncertainties, the total emission from a biogas plant could be as low as <1% or as high as tens of percent. One study measured the overall emissions of a plant with a downwind concentration measurement. This resulted in an estimated 3% which is, not surprisingly, within the aforementioned range.
- *Data sources.* This chapter is based on a relatively small number of articles. There is more information available, but this is not to be found in the open literature. Given the wide ranges in the reported emissions, it would be sensible for anyone interested in quantifying emissions from biogas plants to seek additional information. Therefore, the authors of this chapter recommend a more extensive search to include unpublished reports as well, before drawing final conclusions or planning measurements.

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Biogas digestate quality and utilization

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Abstract: Recycling of the nutrients and organic matter contained in digestate back to the soil is considered the most sustainable utilization of digestate. Safe recycling requires digestate to be of highest quality, not only rich in plant nutrients, but also unpolluted by undesirable matter and compounds of physical, chemical or biological nature. The most important premise of producing high-quality digestate is utilization of high-quality feedstock for the digestion process. Measures for quality management of digestate are implemented in a number of countries as part of national environmental, waste or agricultural legislations. More recently, digestate quality assurance systems are also increasingly used. The overall aim is to secure the production of high-quality digestate and to enhance its subsequent use for agricultural purposes. Digestate can be utilized as it is produced, or it can be further refined through various treatments and technologies commonly known as digestate processing. By digestate processing, marketable biofertilizers can be produced or the nutrient load of the remaining effluent can be decisively reduced, up to discharge quality. A common technology is solid–liquid separation, using screw press separators and decanter centrifuges. Further treatments and technologies can be applied for stabilization of the solid fraction or further refining of the liquid. This chapter emphasizes the main issues related to the quality management of digestate use as a fertilizer, with references to the regulatory framework. The possibilities of improving digestate quality, transportability and marketability through digestate processing are also emphasized. A brief overview of other possible utilizations of digestate and digestate fractions (side streams in digestate processing) is given.

Key words: digestate, quality management, AD feedstock quality, sanitation, heavy metals, organic pollutants, persistent organic pollutants (POPs), physical impurities, pathogen, digestate processing, separation of digestate, decanter centrifuge, screw press, utilization of digestate, biofertilizer.

12.1 Introduction

Digestate, the digested effluent of the biogas production process, consists of the feedstock materials after extraction of biogas through anaerobic digestion (AD). The composition and quality of digestate is therefore highly dependent on the composition and quality of the feedstock used. Because of the content of easily accessible macro- and micronutrients, digestate is a valuable crop fertilizer, suitable to be used in the same way as raw animal slurries. Recycling as fertilizer is considered to be the most sustainable utilization of digestate, as it is able to provide benefits for society in general and for the environment in particular, as well as to help the preservation of limited natural resources such as fossil resources of mineral phosphorus. For use as fertilizer, the digestate needs to be of the highest quality and free of pathogens, chemical and physical impurities and pollutants; this can be achieved by using AD feedstock of controlled quality. Regulatory frameworks, aimed to guarantee the production of high-quality digestate, thus are implemented in countries with developed biogas sectors such as Germany, Denmark, Austria, Sweden Switzerland and the United Kingdom. The regulatory frameworks are regularly updated and increasingly restrictive, in line with new knowledge and experience.

Depending on its end use and on the requirements related to it, the digestate can be used as it is produced (whole digestate) or it can be further refined through a number of treatments and technologies; this is known as digestate processing. The most well-known, used for its simplicity and low cost, is digestate separation into liquid and solid fractions, using decanter centrifuges and screw press separators. There are also more complex processing technologies, of various degrees of technical maturity. Common to all is that they provide volume reduction and separation of the valuable nutrients and fibers from the high volume of water contained in the whole digestate. In addition, the nutrients are often concentrated in order to further reduce transportation costs. When utilization of digestate for agricultural purposes is not feasible because of unsuitable quality or other local conditions, the whole digestate or fractions resulting from digestate processing can be used for other purposes, such as landfill cover in the case of digestate from municipal solid waste, for energy when dewatered or as a raw material for industrial processes.

12.2 Digestate quality

The quality requirements for digestate depend to a large extent on how it is to be used. High quality is the essential pre-condition for use as crop biofertilizer, which is by far the main utilization of digestate. In order to provide quality assurance and thus to enhance the use of high-quality

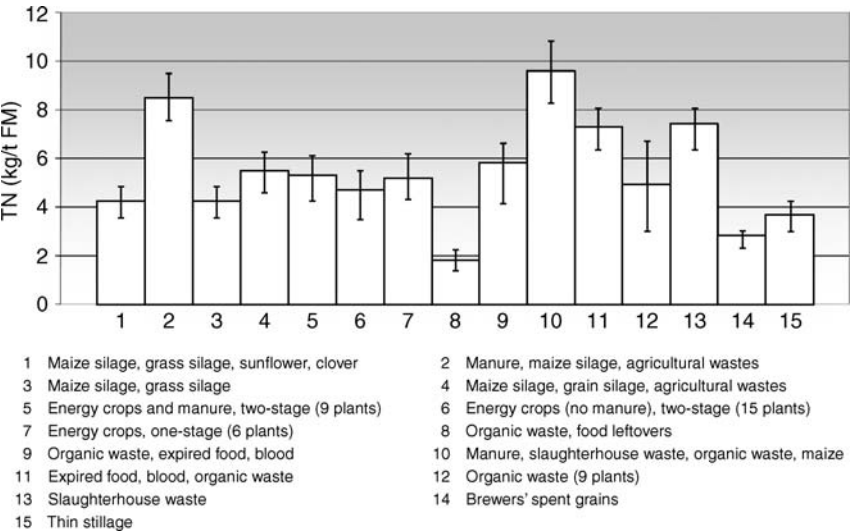
digestate as biofertilizer, many countries have set up regulatory frameworks for the quality of the produced digestate (Al Seadi and Lukehurst, 2012). The quality and use of digestate as a biofertilizer or soil improver are often regulated by soil protection legislation, fertilizer or waste legislation or combinations thereof. In Europe, increasingly strict regulations have been in place for more than 20 years, prescribing limit values for heavy metals, organic pollutants and pathogens in materials used as crops fertilizers and soil improvers, both as EU regulations and national regulations. The national regulations are, in many cases, stricter than the corresponding EU regulation (Al Seadi and Lukehurst, 2012). Countries with developed biogas sectors, such as Austria, Denmark, Germany, Sweden, Switzerland and the UK have taken a step further and implemented specific regulatory frameworks for the quality of digestate aimed to be used as fertilizer. Such frameworks include *inter alia* positive lists of materials suitable as AD feedstock, digestate certification systems and quality standards as well as good practice guidelines. Their aim is to guarantee that digestate intended to be used as fertilizer is of the highest quality and, by this, to encourage its use for agricultural purposes and ensure safe and sustainable practices.

12.2.1 High-quality digestate

High-quality digestate suitable for fertilization purposes is defined by some essential features related to its properties such as: declared content of nutrients, pH value, content of dry matter and organic dry matter, and homogeneity. Equally important are features related to health and safety, including

- purity, requiring that digestate is free of physical impurities (plastic, stones, glass, non-digestible matter, etc.)
- hygiene or sanitization, ensuring that digestate is free of any pathogenic and other undesired biological content
- safety, ensuring it is safe for living organisms and for the environment.

These concerns necessitate strict controls and limitations on the undesirable content of chemical pollutants, both organic and inorganic. From both technical and economic points of view, the only feasible way to ensure production of high-quality digestate, suitable as fertilizer, is to use high-quality feedstock as a substrate for AD. An increasing number of countries in Europe have implemented specific digestate regulations and measures of quality assurance (certification systems for digestate, positive lists of suitable feedstock materials, etc.), aiming to unify the approaches and develop a healthy market for this valuable product (Al Seadi and Lukehurst, 2012). It is important to highlight that the positive lists of feedstock must never exclude the ongoing quality control of the feedstock



12.1 Examples of total nitrogen (TN) concentration in different feedstock types (in kg per ton of fresh matter).

used. The list of feedstock materials must be regularly revised and updated according to the latest knowledge. For more details about AD feedstock, see Chapter 2 of this book.

Digestate quality is positively influenced by well-controlled and stable AD processes and process parameters such as temperature, pH, conductivity, concentrations of volatile fatty acids (VFA), retention time of feedstock, process temperature, etc. More details about these process parameters can be found in Chapter 10 of this book. The quality of digestate can be compromised by inadequate handling and unsuitable storage and application (Al Seadi and Lukehurst, 2012), allowing chemical, physical or biological re-contamination (from un-sanitized materials) or facilitating losses of valuable nutrients by evaporation or leakage.

12.2.2 Digestate characteristics and declaration

The nutrients that are supplied by the feedstock are also present in the digestate (Fig. 12.1). Therefore, the content of plant nutrients in digestate varies between AD plants according to the composition of the feedstock digested and will also vary over time for the same AD plant. This is illustrated in Table 12.1, where the variation of the yearly average composition of digestate produced at Ribe Biogas Plant in Denmark is used as an example. The slight increase in dry matter content during the five years in this particular example was due to measures employed to reduce

Table 12.1 Yearly average values for composition of digestate from the joint co-digestion plant Ribe Biogas A/S, in Denmark

	DM (%)	N total (kg/t)	NH ₄ -N (kg/t)	P total (kg/t)	K total (kg/t)	Mg total (kg/t)	Cu total (g/t)	Ca total (kg/t)
Year 1	5.6	4.7	3.3	0.9	3.7	0.5	9.7	1.5
Year 2	6.4	4.6	3.1	0.9	3.5	0.5	12.8	1.5
Year 3	6.2	5.2	3.4	1.2	4.1	0.8	2.7	2.5
Year 4	5.8	5.0	3.2	1.1	3.3	0.6	11.6	2.0
Year 5	5.8	4.9	3.2	1.1	2.9	0.5	11.8	1.4
Year 6	5.8	4.8	3.2	1.1	3.2	0.5	10.8	1.5

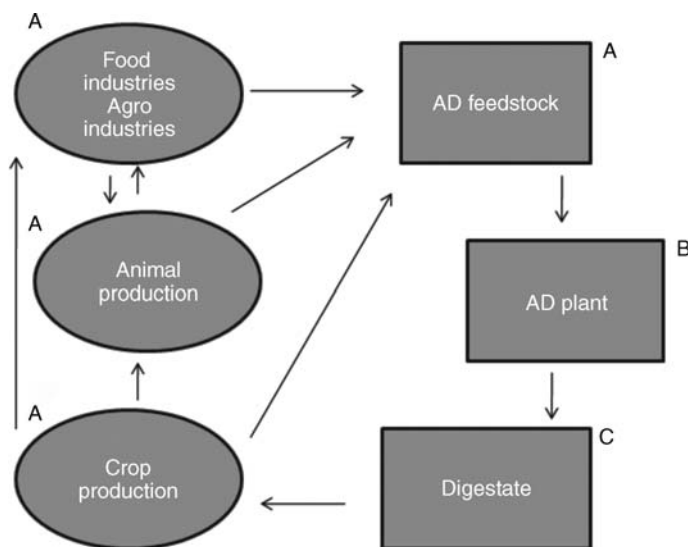
Source: Adapted from Holm-Nielsen *et al.* (1997).

water ingress to wastes (preventing water from roofs, downpipes and farmyards from running into the storage tanks).

When digestate is intended to be used as fertilizer, its composition must be analyzed and declared in order to facilitate accurate dosage of nutrients and allow full integration of digestate in the fertilizer plan of the farm, in line with best farming practices. Declaration is a part of the quality assurance schemes for digestate in many countries. For example, in Denmark, it is required that the digestate declaration contains information about the amount and availability of macro- and micronutrients, the dry matter and organic dry matter content and the pH value of the produced digestate. Digestate has a lower dry matter content than the undigested influent: at least 50% of the dry matter content is converted to methane (CH₄) and carbon dioxide (CO₂). For energy crops, the conversion rate can be as high as 90% (Murphy *et al.*, 2011). Furthermore, the content of ammonium-N (NH₄⁺-N) is high in digestate (around 20% higher than undigested cattle slurry) according to Holm-Nielsen *et al.* (1997).

12.2.3 The concept of digestate quality management

Quality management and quality control of both feedstock and digestate aim to provide assurance that the digestate is suitable and safe for use as fertilizer and that it is perceived as a safe product by crop farmers, food retailers, politicians, decision makers and the general public (Al Seadi and Lukehurst, 2012). Quality management and control measures must be performed throughout the whole closed AD cycle, from production and supply of the AD feedstock until final utilization of the digestate as fertilizer. Quality management implies the use of only high-quality AD feedstock provided through permanent control of feedstock quality, pre-treatment of specific feedstock types, and a stable and robust AD process with ongoing monitoring of the process parameters affecting digestate quality (tempera-



12.2 The closed cycle of digestate production and utilization and the main set-points of digestate quality management: A) AD feedstock; B) AD process; C) digestate declaration, storage and utilization as biofertilizer. Source: Al Seadi and Lukehurst (2012).

ture, retention times, pH, etc.), digestate declaration, suitable handling and storage and best practices of application as biofertilizer (Fig. 12.2).

Digestate is normally used as a fertilizer without further processing (whole digestate), but further refining of the digestate is also possible (see Section 12.3). Digestate processing must be considered as part of the quality management of digestate.

12.2.4 Feedstock quality

As stated earlier, the composition and quality of the digestate is primarily determined by the composition and quality of the feedstock, in combination with the effect of the AD process. Use of high-quality feedstock is therefore the most important starting point for producing digestate suitable and safe to be used as biofertilizer. It is thus crucial that the feedstock materials are not polluted with any unwanted matter or compounds that are able to pass unchanged into the digestate. High quality also means that the materials used as feedstock, by virtue of their composition, supply the anaerobic microorganisms with important nutrients. Strict quality control of the feedstock supplied to the AD plant is therefore a must, and the first step is feedstock description.

Feedstock description

A detailed description of each material supplied as feedstock to an AD plant is a very important part of quality control. The description must comply with national regulations in the area (quality protocols and standards that are set to ensure that digestate is suitable for use as fertilizer) and must also be made available to digestate customers. The basic information that must be provided in the feedstock description is specified in Chapter 2 of this book. The feedstock producer must provide a complete and accurate feedstock description and is responsible for providing the quality as declared. The biogas plant must verify compliance of the documentation with the actual quality of the feedstock. Based on their characteristics and properties and on the intended use of the produced digestate, a specific material can be accepted or excluded as feedstock for AD. For more details on the characterization of feedstocks see Chapter 3.

12.2.5 Managing feedstock quality

Digestate to be used as fertilizer must be a high-quality product, free of physical impurities, pathogenic matter and chemical pollutants. The feedstocks currently used in agricultural biogas plants are usually of high quality. Most unwanted impurities supplied by agricultural feedstock types – except for inert materials such as wood particles, gravel and metals – are normally decomposed or inactivated by AD processes, so they will not affect the suitability and safety of digestate utilization as fertilizer. However, some of the digestible materials used as feedstocks in AD plants contain matter or compounds that are hazardous to living organisms and the environment because they are able to pass undestroyed through the AD system; this is the case for heavy metals and persistent organic pollutants (POPs). Feedstock materials containing hazardous pollutants or other unwanted compounds in concentrations considered to be hazardous for living organisms or for the environment must be excluded from the AD processes where digestate or digestate fractions are to be used for agricultural purposes. Such materials can be used as feedstocks for other biogas processes, where the produced digestate is not used as fertilizer but is used for industrial or energy applications (such as co-combustion for CHP generation) or where the fate of the hazardous matters and compounds is strictly controlled, so any further risks are avoided.

Physical impurities in AD feedstock

Animal manure and slurry, straw, garden waste, crop wastes, energy crops, source-separated organic household waste and food waste are valuable

feedstock materials for the production of quality digestate. Their main limitation is that, depending on their origin and the way they are collected, these feedstocks can contain varying amounts of non-digestible materials such as pieces of plastic, rubber, glass, metal, stones, sand, excessively large pieces of organic material, ligno-cellulosic materials (roots, wood and bark) or other recalcitrant contaminants. The presence of physical impurities in the AD biomass flow can cause problems such as perturbation of operation stability and damage to pumps, pipes, stirrers, etc. If physical impurities are present in the digested material, it will decrease its quality as fertilizer and its public acceptance (e.g. visible plastic pieces from un-degradable household collection bags). Depending on their nature, physical impurities in digestate can also have harmful effects on the environment. In the case of organic household waste, physical impurities are managed most effectively by source separation and separate collection of the digestible fraction in paper or other biodegradable bags. Non-digestible materials can also be removed with the use of physical barriers (screens, sieves, stone traps and protection grills) installed in the pre-storage tanks to prevent access into the AD system. If particle sizes in the feedstock supplied are too large, they can be reduced by chopping, maceration or treatment by other means prior to entering the AD system.

Chemical impurities in AD feedstock

Digestible materials such as sewage sludge, mixed waste (bulk collected waste) or domestic wastewaters can contain various amounts of unwanted chemical matter (heavy metals and organic compounds), of which some are POPs. Chemical pollutants can also be present in some industrial organic wastes, household waste and even in food waste. Agriculturally derived feedstock materials in most European countries, where strict legislation bans the use of pesticides from the United Nations list of POPs, do not contain such pollutants, although trace amounts of other pesticides, antibiotics and chemicals used in agriculture can be present in agricultural feedstock. In developing countries, where pesticides classified as POPs are still used in agricultural practices (e.g. DDT and HCH), the occurrence of POPs in agricultural feedstock for AD is likely to be much higher (United Nations Environment Programme, 2010; Stockholm Convention, 2011). POPs, including polycyclic aromatic hydrocarbons (PAHs), are recognized as being directly toxic to biota and can progressively accumulate higher up the food chain such that chronic exposure of lower organisms to much lower concentrations can expose predatory organisms, including humans and wildlife, to potentially harmful concentrations (European Environment Agency, 2011).

12.2.6 Sewage sludge

The impact of land application of sewage sludge from waste treatment plants can be controversial. Sewage sludge is a highly complex digestible material, with a methane potential similar to that of cattle and pig slurry. Its composition varies significantly with geographical area, consumption patterns and local environmental and waste treatment policies (Smith, 2009). Recycling sewage sludge to agricultural land is regarded in some countries as a pragmatic approach to managing the sludge generated from urban wastewater and the cheapest disposal method for wastewater treatment plants. The European Commission permits monitored and well-regulated use of sewage sludge on agricultural soils as a fertilizer, provided that it does not pose any threat to the environment or to animal and human health (Smith, 2009). The acceptance of this practice varies significantly among European countries and has declined significantly in many places, leading to banning of the use of sludge in agriculture (Smith, 2009) in countries such as Switzerland, the Netherlands and Austria.

The same divergence of opinions can be found in the scientific literature concerning sewage sludge. Smith (2009) states that 'recycling sewage sludge on farmland is not constrained by concentrations of OCs' (organic contaminants) and indicates that 'the chemical quality of sludge is continually improving and concentrations of potentially harmful and persistent organic compounds have declined to background values'. Stevens *et al.* (2003) report that data on the concentrations of certain classes of persistent organic compounds in digested sewage sludge are scarce. They also indicate that, in line with data from other countries, very high concentrations of PAHs and short- and medium-chained polychlorinated alkanes, exceeding many times the EU limit values for such compounds, are found in slurry from wastewater plants in the UK. Nevertheless, according to Clarke and Smith (2011), most of the existing risk assessments demonstrate that use of digested sewage sludge as fertilizer does not place human health at risk, from the point of view of the organic contaminants studied so far, but also note that 'continued vigilance in assessing the significance and implications of "emerging" OCs in sludge is necessary to support and ensure the long-term sustainability and security of the beneficial agricultural route for biosolids management'. According to Clarke and Smith (2011), two classes of POPs require research priority – perfluorinated compounds (PFCs) and polychlorinated alkanes (PCAs) – which, due to their unique chemistry that facilitates a degree of water solubility, are likely to cause exposure through all pathways.

Mogensen *et al.* (1999) indicate that the AD process can have a certain effect on the decomposition of some POPs belonging to PAHs, if some special process conditions are fulfilled. The special conditions refer to the

presence of relevant microbial populations inside the digester, which are able to metabolize the respective compounds at specified environmental conditions for these microbial populations. The organic compounds must be accessible to the microorganisms and the composition and the amount of feedstock mixture must be maintained constant throughout the process. The microorganisms need an adaptation period to the substrate.

There are 50 million chemicals entered in the Chemical Abstracts Registry and this number is continuously increasing. Of these, 143,000 chemicals are registered with the European Chemicals Agency for industrial use (Clarke and Smith, 2011). The UN list of POPs is constantly updated as new compounds are studied and their long-term effects are documented (United Nations Environment Programme, 2010; Stockholm Convention, 2011). A recent EU report (European Commission/JRC-IPTS, 2011) emphasizes that there are important knowledge gaps concerning the scientific base for setting the limit values for chemical pollutants in waste-derived materials as well as insufficient toxicological and eco-toxicological risk assessments. The issue of application of sewage sludge on land therefore remains open and ongoing research is expected to clarify sustainable biosolids management.

In practice, it is impossible to perform screening of a broad spectrum of chemical pollutants at reasonable costs. It is therefore widely accepted that quality assurance of digestate can only be provided through a responsible selection of the AD feedstock materials used, combined with permanent control of their quality.

12.2.7 Legal frameworks for control of chemical pollutants

The levels of chemical pollutants in digestate produced from high-quality agricultural feedstock are in general much lower than the limit values prescribed by legislations (Al Seadi and Lukehurst, 2012). Tables 12.2 and 12.3 show examples of limit values for heavy metals and organic pollutants in waste-derived products applied as fertilizers; they are also applicable to digestate used for agricultural purposes.

12.2.8 Pathogens and other unwanted biological impurities

The AD process is very effective in terms of inactivation of most pathogenic matter such as bacteria, viruses, intestinal parasites, weed and crop seeds, and crop diseases. Nevertheless, exclusion of feedstock contaminated with high-risk biological material is an important measure in digestate quality control (hence the positive lists in some countries) and applies to all feedstock types, including manure and other agricultural feedstock. No biomass should be supplied from farms where there are serious animal health problems. Strict pathogen control in waste products used as fertilizers

Table 12.2 Example of limit values of heavy metals (mg/kg DM) in waste-derived products applied as fertilizers

Country/region	Cd	Pb	Hg	Ni	Zn	Cu	Cr
Austria ^a	3 (10)	100 (600)	1 (10)	100 (400)	– (3000)	– (700)	100 (600)
Canada	3	150	0.6	62	500	100	210
Denmark	0.8	120	0.8	30	4000	1000	100
Finland	1.5	100	1	100	150	600	300
France	20	800	10	200	3000	1000	3000
Germany	10	900	8	200	2500	800	900
Ireland	20	750	16	300	2500	1000	1000
Norway	2	80	3	50	800	650	100
Sweden ^b	1	100	1	50	800	600	100
Switzerland ^c	1/0.7	120/45	1/0.4	30/25	400/200	100/70	70/na
The Netherlands	1.25	100	0.75	30	300	75	75
United Kingdom ^d	1.5	200	1	50	400	200	100

^a Values in brackets express g/ha limited nutrient loads for a 2-year period (Düngemittelverordnung, 2004)

^b Swedish digestate certification

^c Swiss guidelines for utilization of compost and digestate

^d Publicly Available Standard (PAS) 110

Source: Al Seadi and Lukehurst (2012).

Table 12.3 Examples of national limit values of organic pollutants in waste-derived products applied as fertilizers

Organic pollutant	Country		
	Austria (Düngemittelverordnung, 2004)	Denmark (Danish Ministry of Environment and Energy, 2000)	Switzerland
PAHs	6 mg/kg DM	3 mg/kgDM	4 mg/kg DM ^a
PCDD/F	20 ng TE/kg DM	—	20 ng ITEC/kg DM ^a
Chlorinated pesticides (HCH, DDT, DDE, etc.)	0.5 mg/kg product	—	—
PCB	0.2 mg/kg DM	—	—
AOX	500 mg/kg DM	—	—
LAS	—	1300 mg/kgDM	—
NPE	—	10 mg/kg DM	—
DEPH	—	50 mg/kg DM	—

^a I-TEC: international toxicity equivalents.

Source: Adapted from Al Seadi and Lukehurst (2012).

helps to prevent pathogen and disease transmission between animals, humans and the environment. Denmark was the first country in Europe to introduce veterinary regulations in this regard in 1989 and since then many other European countries have introduced similar regulations.

Table 12.4 Comparison of decimation time T_{90} (time for destruction of 90% of pathogens) of some pathogenic bacteria in AD system and untreated animal slurry system

Bacteria	AD system		Untreated slurry system	
	53°C T_{90} (hours)	35°C T_{90} (days)	18–21°C T_{90} (weeks)	6–15°C T_{90} (weeks)
<i>Salmonella typhimurium</i>	0.7	2.4	2.0	5.9
<i>Salmonella dublin</i>	0.6	2.1	—	—
<i>Escherichia coli</i>	0.4	1.8	2.0	8.8
<i>Staphylococcus aureus</i>	0.5	0.9	0.9	7.1
<i>Mycobacterium paratuberculosis</i>	0.7	6.0	—	—
Coliform bacteria	—	3.1	2.1	9.3
Group D streptococci	—	7.1	5.7	21.4
<i>Streptococcus faecalis</i>	1.0	2.0	—	—

Source: Compiled after Bendixen (1994, 1995, 1999).

12.2.9 Controlled inactivation of animal pathogens

The AD process has a sanitization effect, being able to inactivate most of the common pathogens present in the feedstock mixture inside the digester (Table 12.4). The inactivation of pathogens occurs as a result of a combination of constant process temperatures (thermophilic or mesophilic) and retention times of feedstock, in interaction with other parameters of the micro-environment inside the digester.

The sanitation efficiency of AD can be measured using indicator organisms. One of the most common of these is *Streptococcus faecalis* (FS) (Bendixen, 1994, 1995, 1999). A reduction of the amount of FS per gram biomass of 3–4 log 10 units corresponds to the combined effect of digestion temperature and time of exposure able to destroy most of the pathogens such as *Salmonella* sp. and Pestivirus (ssRNA / Flavivirus) and to reduce the viability of many parasites such as *Ascaris*.

Operators must select process temperatures and retention times that are appropriate for the kind of feedstock to be digested. In the case of existing AD plants, the choice of allowable feedstock depends to a large extent on the type of process applied (e.g. mesophilic or thermophilic) and the existing pre-treatment facilities at the plant. The combination of process temperature and retention time is the most important pathogen inactivation factor. Martens *et al.* (1998), Engeli *et al.* (1993) and Carrington (2001) indicate that the degree of pathogen inactivation is more complex, occurring from a combined effect of temperatures and retention time with other process parameters such as pH, redox potential and NH_3 concentration inside the digester. Combinations of thermophilic or mesophilic process temperatures

Table 12.5 Combinations of temperatures and MGRTs for sanitation, equivalent to 70°C for 1 hour. Example from Denmark

Temperature (°C)	MGRT at thermophilic temperature (hours) ^a	MGRT by treatment in batch sanitation tank (hours)	
		Before thermophilic digestion ^a	Before mesophilic digestion ^b
52.0	10		
53.5	8		
55.0	6	5.5	7.5
60.0		2.5	3.5

^a Hydraulic retention time (HRT) in the digester must be at least 7 days.

^b Temperature of 20–32°C; HRT minimum 14 days.

Source: Compiled after Bendixen (1994, 1995, 1999).

and retention time inside the digester can provide pathogen reduction in animal manure/animal slurries and in vegetable wastes equivalent to the EU sanitation standard of 70°C for 1 hour (Bendixen, 1994, 1995, 1999; European Commission, 2009). The hydraulic retention time (HRT) represents the average time (usually expressed in days) the feedstock resides inside the digester, at process temperature, and is given by

$$\text{HRT (hours or days)} = \frac{\text{Digester volume (m}^3\text{)}}{\text{Influent flow rate (m}^3\text{/h or m}^3\text{/day)}}$$

The HRT influences digestate quality and depends to a large extent on the digestibility of the feedstock mixture.

In continuous flow stirred digesters, it is possible that portions of the feedstock mixture pass through the digester by short cuts. The minimum guaranteed retention time (MGRT) is therefore the minimum time (usually measured in hours) that *any portion of the feedstock* resides inside the digester at constant process temperature. Depending on the feedstock materials digested, combinations of process temperatures and MGRT are allowed (Table 12.5) to provide sanitation equivalent to pasteurization (70°C for 1 hour) for feedstock types where other specific pathogen reduction measures are not required by other regulations. Table 12.5 shows that a sanitation equivalent to 70°C for 1 hour occurs at 52°C and a MGRT of 10 hours, when the HRT is a minimum of 7 days. The specific combinations of temperatures and MGRT/HRT must be respected.

Occurrences of bovine spongiform encephalopathy (BSE) and foot and mouth disease (mononucleosis) have led to the enforcement of strict rules on the treatment and further use of animal by-products, aiming to prevent further spread of such diseases. Since 2002, the utilization of animal by-products not intended or suitable for human consumption is regulated in

Europe by the Animal By-product Regulations (ABPR); further information given in Chapter 2.

Although most of the common pathogens and common viruses are inactivated during the AD process (mesophilic and thermophilic) (Bendixen, 1994, 1995, 1999; Lund *et al.*, 1996), supplementary sanitation is required for some specific feedstock types. Batch pre-sanitation by pasteurization or pressure sterilization is done for veterinary safety reasons, but also has the economic advantage of avoiding the high costs of pasteurizing the whole digester volume.

12.2.10 Inactivation of plant pathogens and weed seeds

Mesophilic digestion offers significant or total destruction of most disease-spreading spores that could affect crops (Zetterstrom, 2008; Lukehurst *et al.*, 2010). Overbeek and Runia (2011) indicate that mesophilic digestion effectively inactivates plant pathogens. Potato nematodes *Globoderar ostochiensis* and *G. pallida*, are destroyed in a few days at 35°C. Tests made with *Fusarium oxysporum*, which affects maize and cereal crops, showed that it was inactivated by mesophilic AD in one day, and no spores were present in the final digestate (Overbeek and Runia, 2011). *Plasmodiophora brassicae*, which is much more difficult to inactivate according to Engeli *et al.* (1993), did not survive after 14 days at 55°C. Research results from Denmark (ICROFS/BioConsens, 2011) show that AD effectively reduces the germination power of plant and weed seeds present in feedstock.

12.3 Processing of digestate

12.3.1 Reasons for the processing of digestate

After removal from the digester, digestate can be used without any further treatment. The storage, transport, handling and application of digestate as a fertilizer results in significant costs for farmers compared with its fertilizer value; this is due to the large volume and low dry matter content. The costs increase further with investment in slurry storage capacities, which are required by national environmental regulations in countries like Denmark, Germany and France where the period of fertilizer application is limited to the growing season and the amount of nutrients applied per unit of agricultural land is restricted by pollution control regulations. The European nitrate directive also limits the annual nitrogen load which can be applied to agricultural land (European Commission, 1991). As digestate has a high content of easily available plant nitrogen this influences the amount of digestate that can be applied. Such strict legislative frameworks,

which seek to protect the environment, may necessitate transport and redistribution of nutrients away from intensive areas. These conditions make digestate processing attractive.

Digestate processing involves the application of different technologies to the effluent from anaerobic digesters. The technologies applied are mostly comparable to existing technologies for manure processing, sewage sludge treatment or wastewater treatment. Digestate processing can be approached in two ways. The first is digestate conditioning, which aims to produce standardized biofertilizers (solid or liquid) in which the quality and marketability of the digestate is improved. The second can be described as digestate treatment; similar to wastewater treatment, it is applied in order to remove nutrients and organic matter from the effluent and allow discharge into a sewage system, an on-site wastewater treatment plant or a receiving stream. In most cases it will be necessary to carry out both conditioning and treatment in order to establish a viable digestate processing concept.

12.3.2 Overview of technologies for the processing of digestate

Digestate processing can be partial, usually targeting volume reduction, or it can be complete, refining digestate to pure water, fibers/solids and concentrates of mineral nutrients. The first step in digestate processing is to separate the solid phase from the liquid. The solid fraction can subsequently be directly applied as fertilizer in agriculture or it can be composted or dried for intermediate storage and enhanced transportability. To improve solid–liquid separation, flocculation or precipitation agents are commonly applied.

Partial processing uses relatively simple and cheap technologies. For complete processing, different methods and technologies are currently available, with various degrees of technical maturity and requiring high energy consumption and high costs. For nutrient recovery, membrane technologies such as nano- and ultra-filtration followed by reverse osmosis are used (Fakhru'l-Razi, 1994; Diltz *et al.*, 2007). Membrane filtration produces a nutrient concentrate and purified process water (Castelblanque and Salimbeni, 1999; Klink *et al.*, 2007). The liquid digestate can also be purified through aerobic biological wastewater treatment (Camarero *et al.*, 1996). However, because of the high nitrogen content and low biological oxygen demand (BOD), addition of an external carbon source may be necessary to achieve appropriate denitrification. A further possibility for concentrating digestate is evaporation with waste heat from the biogas plant. For reducing the nitrogen content in the digestate, stripping (Siegrist *et al.*, 2005), ion exchange (Sánchez *et al.*, 1995) and struvite precipitation

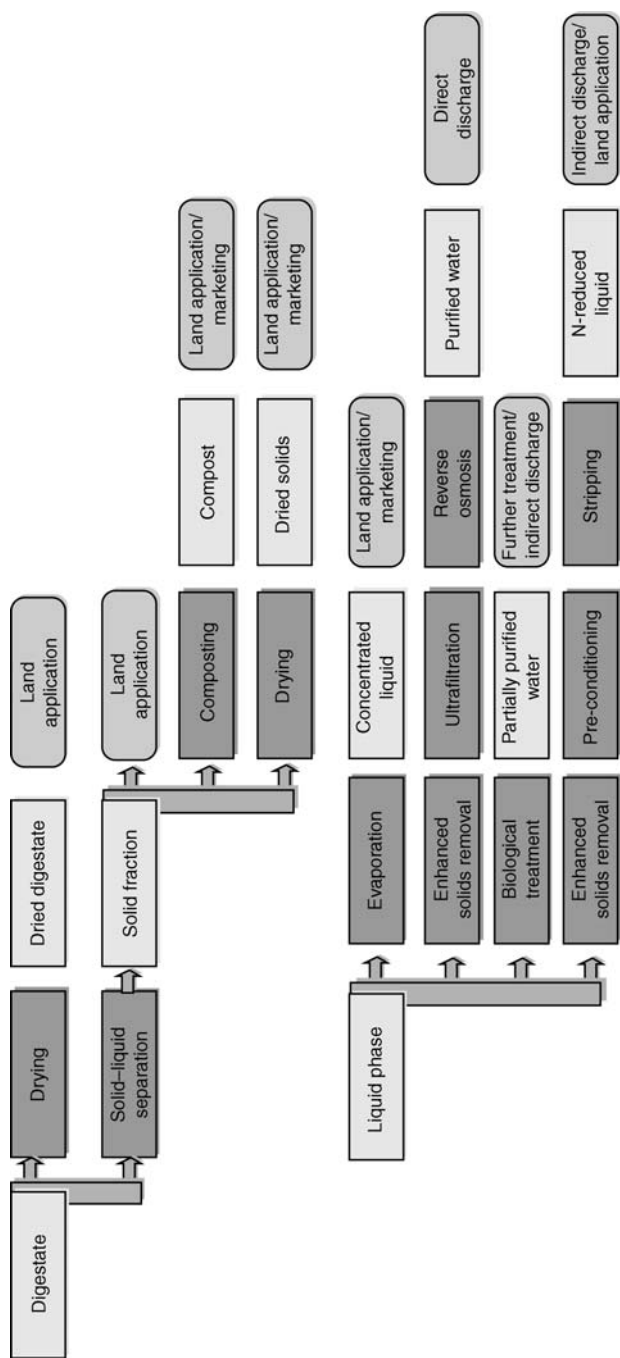
(Uludag-Demirer *et al.*, 2005; Marti *et al.*, 2008) have been proposed. Whatever process is applied, advanced digestate processing in most cases requires high chemical and energy inputs. Together with increased investment costs for appropriate machinery, considerable treatment costs may result. In the following text, distinctions will be made between unprocessed digestate and digestate fractions (co- and by-products from digestate processing). An overview of digestate processing technologies is given in Fig. 12.3.

12.3.3 Solid–liquid separation of digestate

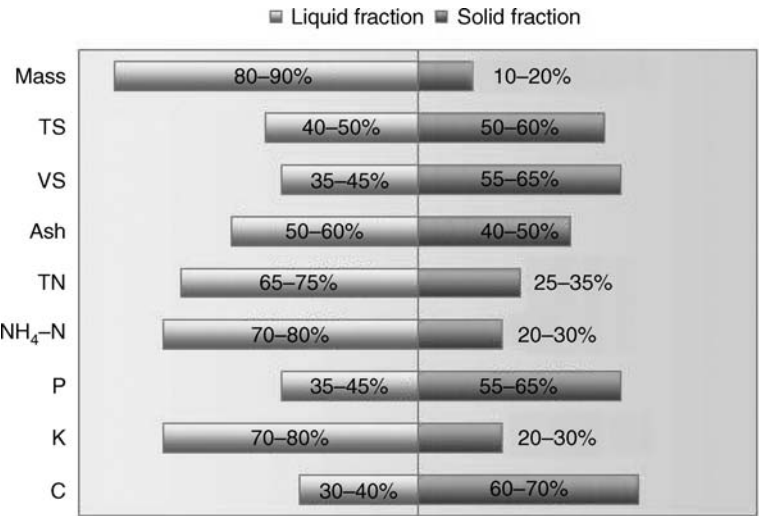
The first step in any digestate processing system is solid–liquid separation: the partitioning of liquid digestate into high dry matter solid material (fiber, sludge) and low dry matter liquid. Both fractions can be used without further treatment as fertilizer. Solid–liquid partitioning separates most of the phosphorus with the solid fraction and most of the nitrogen with the liquid fraction, which helps the management of plant nutrients in digestate by enabling separate dosage of phosphorus and nitrogen and transport and application of the phosphorus to other areas.

The phosphorus-rich fiber fraction can be applied or sold as a phosphorus-rich fertilizer; it can be dried and pelletized, composted and used as soil improver, used for industrial purposes (composite materials) or even incinerated for energy recovery. As shown in Fig. 12.4, the liquid fraction contains the main part of nitrogen (N) and potassium (K) and this fraction can be applied as liquid fertilizer or mixed with a high solids feedstock and re-fed to the digester. In countries where phosphorus is the rate limiting nutrient for eutrophication (e.g. Ireland) solid–liquid separation is advantageous as the solid fraction, may be exported and the liquid fraction containing little phosphorus, may be land applied. The various technologies for further processing of the solid and liquid fractions are described in Sections 12.3.4 and 12.3.5.

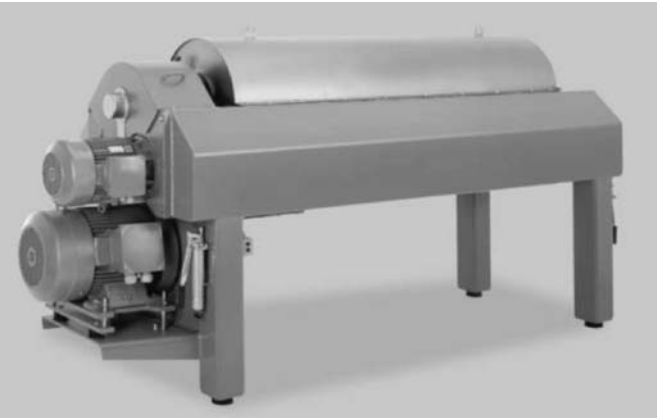
A variety of solid–liquid separation technologies are available on the market; these include decanter centrifuges, screw press separators, bow sieves, double circle bow sieves, sieve belt presses and sieve drum presses. The decanter centrifuge and the screw press separator have gained popularity, especially among farmers who need to export their excess of nutrients to other areas. Screw press separators are mainly used in energy crop digestion, where the digestate is rich in fibers. Decanter centrifuges are used in manure co-digestion (as in Denmark) and also in municipal or industrial waste treatment plants.



12.3 Overview of different options for processing of digestate.



12.4 Distribution of the principal constituents after solid–liquid separation (adapted from Bauer *et al.*, 2009).



12.5 Decanter centrifuge (DANETV, 2010).

Solid–liquid separation of digestate by decanter centrifuge

Decanter centrifuges can be used to separate the majority of the phosphorus contained in digestate with the fiber fraction (Møller, 2001). Several commercial brands of decanter centrifuges are now utilized for digestate separation, with similar performances; an example is shown in Fig. 12.5.

Tables 12.6 and 12.7 show test results of the GEA Westfalia decanter centrifuge (DANETV, 2010). Testing was carried out on five batches, for a minimum of 4 hours each, with a fixed start and end time for each batch.

Table 12.6 Digestate separation by decanter centrifuge: average content of total solids, ashes, volatile solids, suspended solids and pH

	Total solids (%)	Ash content (%)	Volatile solids ^a (%)	Suspended solids (mg/l)	pH (ppm)
Input digestate	4.85	1.46	3.39	35,000	7.64
Liquid output fraction	2.31	0.82	1.49	8,400	7.94
Solid output fraction	27.66	6.46	21.20	Not relevant	8.12

^a Values for volatile solids are not measured but calculated as the difference between total solids and ash content.

Source: Adapted from DANETV (2010).

Table 12.7 Digestate separation by decanter centrifuge: average concentrations of nutrients

	Total nitrogen (kg/t)	Ammonium nitrogen (kg/t)	Organic nitrogen ^a (kg/t)	Total phosphorus (kg/t)	Total sulfur (kg/t)
Input digestate	4.08	2.87	1.21	0.94	0.42
Liquid output fraction	3.49	2.63	0.86	0.31	0.29
Solid output fraction	8.15	4.50	3.65	6.52	1.56

^a Values for organic nitrogen are not measured but calculated as the difference between total N and ammonium N.

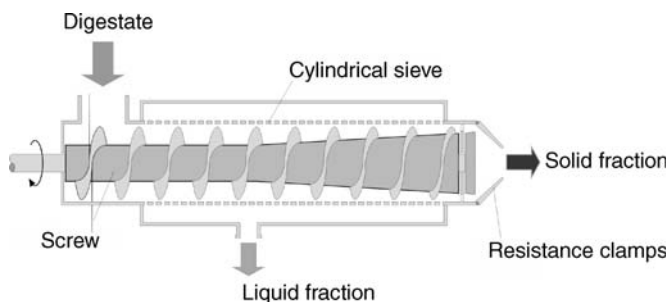
Source: Adapted from DANETV (2010).

Table 12.8 Example of digestate separation by decanter centrifuge

	Digestate	Fiber fraction	Liquid fraction
Quantity (kg)	1000	80	920
Dry matter content 2.8% (kg)	28	24	4
Water content (kg)	972	56	916
Total N nitrogen (kg)	5	1.25	3.75
NH ₄ -N (kg)	4	0.3	3.7
Phosphorus (kg)	0.9	0.7	0.2
Potassium (kg)	2.8	0.2	2.6

Source: Adapted from Jørgensen (2009).

For each batch, the weight or volume of input digested biomass, liquid output fraction and solid output fraction was measured and concentrations of solids and nutrients were determined by analyzing representative samples of the inlet and the two outlet flows. During treatment of the five batches, the decanter centrifuge treated 283 m³ of digestate, corresponding to an average capacity of 13.72 m³ biomass treated per hour. A specific example of the effect of digestate separation by decanter centrifuge is given in Table 12.8.



12.6 Set-up of a screw press separator.

Solid–liquid separation of digestate by screw press separator

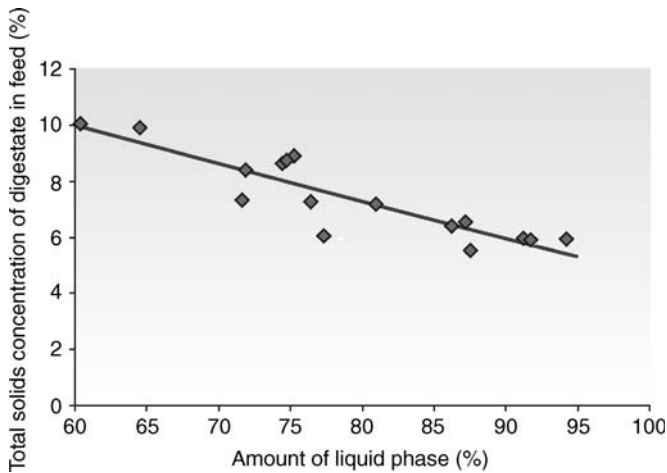
Screw press separators are often used in medium to large-scale biogas plants with high fiber content in the digestate, as is the case for energy crop digestion. Figure 12.6 shows the set-up: a screw presses fibers against the cylindrical sieve; the liquid fraction drains through the sieve; because of the increasing diameter of the screw, the pressure increases with the advance of fibers in the separator; finally, the solid fiber fraction exits at the end of the separator, where the resistance can be adjusted mechanically.

Unlike decanter centrifuges, screw press separators cannot separate sludge fractions from the digestate. If the digestate contains mainly fiber fractions, the amount of solid fraction that will accumulate is dependent on the dry matter content of the digestate. Bauer *et al.* (2009) found a correlation between dry matter content in the digestate and the amount of solid fraction accumulated (Fig. 12.7).

The separation efficiency of different components in the digestate has been investigated, as shown in Table 12.9. As mentioned earlier the separation efficiency will always depend on the dry matter and fiber content in the digestate. The advantages of the screw press separator over the decanter centrifuge are low investment costs (approx. 20,000€ for a 500 kW_{el} plant) (Bauer *et al.* 2009) and low energy consumption (0.4–0.5 kWh/m³) (Fuchs and Drosig, 2010).

Use of precipitating agents for enhancement of separation

The use of chemicals for enhancement of separation is a relatively new approach for treating digestate or animal manure, though it has become a widely accepted method for the treatment of municipal and industrial wastewater. The chemicals most commonly used for phosphorus removal from wastewaters are aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3$), ferric chloride (FeCl_3), ferric sulfate ($\text{Fe}_2(\text{SO}_4)_3$) and lime ($\text{Ca}(\text{OH})_2$). For further agglomeration of coagulated particles, the addition of polymers may be needed under



12.7 Relation between dry matter content of digestate and amount of solid fraction accumulated (Bauer *et al.*, 2009).

Table 12.9 Typical separation performance of screw press separators

	Percentage of fresh matter (%)	Degree of separation (%)						
		TS	VS	COD	NH ₄ -N	TN	PO ₄ -P	K
Solid fraction	10.0	48.1	56.3	48.8	9.2	17.0	21.8	10.0
Liquid fraction	90.0	51.9	52.4	51.2	82.0	83.0	78.0	90.0

Source: KTBL (2008).

certain circumstances (Westerman and Bicudo, 1998). Chemical precipitation of animal manure involves the addition of chemicals to alter the physical state of dissolved and suspended solids to facilitate removal (Zhang and Westerman, 1997; Westerman and Bicudo, 1998).

12.3.4 Further processing of the solid fraction

After solid–liquid separation and depending on the feedstock type, the solid fraction can be either directly used as a soil improver or it can undergo further processing. The latter includes composting or further drying.

Composting

Composting will require additional organic fibrous material (such as woodchips) as the digestate is usually too wet and too dense for direct composting. A special application of composting is vermiculture using

earthworms. In general, composting of the solid fraction increases the concentration of nutrients in the solid fraction, but also may result in nitrogen loss.

Drying

Besides composting, solid digestate can be also dried by different technologies such as solar radiation or excess heat from a CHP plant. The dried material can be used in the horticultural and gardening sectors, as is or in pelletized form. The material can be used also in nurseries or for special cultivation systems such as mushroom production.

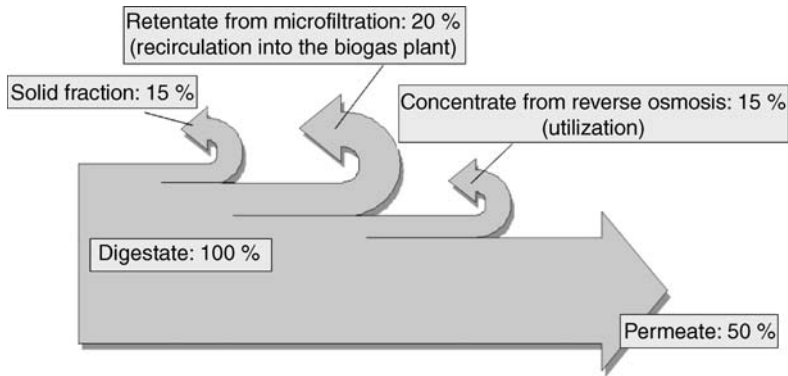
Local policy and markets influence the marketability of compost or dried digestate. Quality standards and legislation on fertilizers and compost products need consideration. Especially for waste digestate, concentrations of heavy metals and other chemical pollutants may be a barrier to the sale of digestate products. Legal frameworks in most countries stipulate the quality conditions for the marketing of waste-based digestate products.

12.3.5 Further processing of the liquid fraction

The liquid fraction can be applied on soils as nitrogen-rich liquid fertilizer without any further processing. It can also be re-fed to the AD reactor, as described in Section 12.4.2. The most important technologies for further treatment of the liquid fraction of digestate are ammonia removal, membrane filtration, aerobic treatment and evaporation.

Ammonia stripping

Among the intermediate processing steps to reduce nitrogen concentration in digestate, ammonia stripping seems to be one of the preferable technologies. Compared to struvite (magnesium ammonium phosphate) precipitation, which requires the addition of magnesium and phosphate to allow a maximum of 88% ammonia removal, a pH of 9.5 and an ammonium: magnesium:phosphate molar ratio of 1:1.25:1 (Miles and Ellis, 1998), ammonia stripping has the advantage that it does not require expensive chemicals. Due to the clogging problems in state-of-the-art packed stripping columns, the trend seems to be towards more simplified stripping vessels. The big advantage of ammonia stripping is that a standardized nitrogen fertilizer product can be recovered. In addition, such a fertilizer liquid can be used to enrich other digestate fractions in digestate processing to a standardized nitrogen concentration, which can increase their marketability.



12.8 By-product accumulation in membrane purification processes of digestate.

Membrane filtration

When applying membrane technology to the liquid fraction of digestate, enhanced solids removal has to be performed first. This is a crucial point in membrane purification processes, alongside of membrane fouling. Decanter centrifuges are usually used in the first solid–liquid separation step and precipitating agents are often added for increased solids removal. The next step is ultrafiltration and, finally, reverse osmosis is used for removal of ammonia and COD (chemical oxygen demand). Normally, three steps of reverse osmosis are needed to reach discharge levels for ammonia. A drawback of such membrane purification processes is that only a limited amount of the digestate will be purified water; about 50% of the digestate is accumulated as by-products (see Fig. 12.8). As an alternative, the last reverse osmosis step can be replaced by ion exchange in which the solid fraction, ultrafiltration retentate and reverse osmosis concentrate are accumulated. In order to reduce amounts, the ultrafiltration retentate is often recycled into the biogas plant and/or the solid–liquid separation step. Membrane purification is quite expensive and requires a considerable amount of energy.

Aerobic treatment

In an ideal situation, the liquid fraction of the digestate can be treated together with another wastewater (rich in carbon) in an aerobic wastewater treatment plant. If this is not the case, an external carbon source will have to be added because, due to the high ammonia content, the bacteria need excess carbon in order to carry out the denitrification step. Apart from the nitrogen problem, residual COD and the color of the treated effluent (turbidity) make it difficult to meet required discharge levels. In addition, aerobic wastewater treatment means high investment and operation costs.

Table 12.10 Example data for the performance of evaporation

	DM (%)	Organic DM (%)	TN (g/kg)	PO ₄ -P (g/kg)	COD (g/kg)
Inflow	3.1	1.7	3.1	0.3	45
Concentrate	11.0	8.3	9.0	1.0	108
Condensate	0.05	0.05	0.04	0.0	<1

Source: Adapted from Heidler (2005).

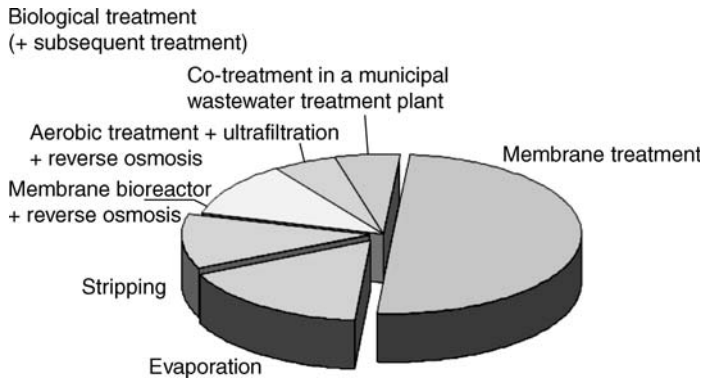
The Anammox process

For the removal of ammonia, the Anammox (anaerobic ammonium oxidation) process can be applied. This is a microbial process that takes place in many natural environments and is also the trademarked name of the ammonium removal technology subsequently developed. The Anammox process is performed by bacteria, with *Planctomyces* and *Pirellula* being the most well-known genera, and consists of two steps that take place in the same reactor: (I) partial nitrification performed by ammonia-oxidizing bacteria; (II) conversion of the resulting ammonium and nitrite to dinitrogen gas and about 15% nitrate (not illustrated), performed by Anammox bacteria, according to:



Evaporation

The evaporation of digestate can be an interesting solution if sufficient waste heat is available at the biogas plant. A considerable amount of the solids should be removed beforehand. In technical-scale applications (such as energy crop digestion) this is often done by combining screw press separators and vibration sieves to remove fibers and thus reduce clogging of the heat exchangers. However, a considerable amount of cleaning will still be needed. By evaporation, a nutrient-rich concentrate is produced and a condensate is recovered. The ambition is to have low nitrogen concentrations in the condensate and high nitrogen concentrations in the concentrate. Considerable amounts of sulfuric acid are added to reduce the evaporation of ammonia, which implies high costs. Apart from that, the produced condensate does not meet direct discharge levels (see Table 12.10). If direct discharge is required, the condensate can be purified via a reverse osmosis step. In conclusion, digestate evaporation requires the use of considerable chemicals and the availability of waste heat, direct discharge levels of the condensate cannot normally be obtained.



12.9 Overview of the distribution of industrial-scale applications of further treatment of the liquid fraction of digestate in Germany, Austria and Switzerland in 2009.

Combined processes

There are several systems for complete processing of the digestate into concentrated fertilizer products by combining solid–liquid separation with one or more refinement steps of varying degrees of technical maturity. There are agricultural biogas plants operating with digestate processing facilities in Denmark and more plants are considering establishing such facilities (Al Seadi and Møller, 2003). There are several industrial-scale plants with combined digestate processing concepts in Germany. Figure 12.9 gives an overview on the distribution of technologies for the further treatment of the liquid fraction of digestate in Germany, Austria and Switzerland.

12.3.6 Advantages and limitations of digestate processing

Intensive animal farming has come under increasing legislative pressure over recent decades as requirements for environmental protection through better nutrient management have necessitated export and redistribution of the excess nutrients and regulated the application of fertilizers. This has led to an increase in the costs of nutrient management in both manure and digestate, as their high volume and low dry matter content made transport over long distances very expensive. Partitioning digestate into a solid fraction and a liquid fraction, where only the solid fraction is exported, thus has the potential to reduce transport and application costs of digestate. Separation by decanter centrifuges and screw press separators has gained popularity because of the simplicity, efficiency and low cost of these systems. Several combined technologies and separation concepts have been developed, of which some are still documented and implemented at full scale while others are still in various stages of development. Biogas plants

handling large volumes of low dry matter biomass can benefit from a volume reduction by separation. By mixing different digestate fractions (e.g. ammonia liquid from stripping), the concentration of some nutrients can be adjusted and this can be a considerable advantage for the marketing of the product as biofertilizer.

12.4 Utilization of digestate and digestate fractions

Digestate or digestate fractions can be used as agricultural fertilizers or high-quality compost and soil improvers, re-digested in the biogas plant, used for energy production or other applications (e.g. industrial products) or even as animal feed. The suitability of digestate for various uses is highly dependent on its composition and quality and the local nutrient situation. Digestate is, first of all, a valuable biofertilizer, rich in plant nutrients and with great potential worldwide as a substitute for mineral fertilizers. The quality requirements related to digestate use as fertilizer were addressed in Section 12.2. Apart from unsuitable quality, specific local conditions (e.g. regional excess of nutrients in intensive agricultural areas or in highly populated areas) can make land application of digestate problematic as it would add further nutrients to the local environment. In such cases, other solutions for digestate processing and utilization must be applied.

12.4.1 Digestate as agricultural fertilizer and soil improver

Digestate as fertilizer

Recycling as a crop fertilizer or soil improver is the most sustainable utilization of digestate. The concept of closing the nutrient cycle and substitution of fossil fertilizers are the main drivers. Safe agricultural recycling requires digestate to be of highest quality. The simplest way to use digestate as fertilizer is to apply the 'whole digestate' as it is removed from the digester onto crop fields, without further treatment. The amounts and timing of application are regulated by national fertilizer management legislations and good agricultural practices, and depend largely on the soil properties and the crops being cultivated. To prevent loss of nutrients and pollution problems, most European countries have adopted the prescriptions of the European nitrate directive (European Commission, 1991) and have taken measures to limit nitrate input onto land to a maximum amount of 170 kg/ha per year and implement bans for fertilizer application during the winter season. The seasonal restriction means that, in Europe, digestate must be stored for four to nine months, depending on the national requirements. In other climates, with continuous plant growth throughout the year, storage requirements may be shorter. In all cases, sufficient

digestate storage capacity needs to be established to accommodate digestate production, since its land application must be specifically adjusted to the season of plant growth.

Digestate is applied as fertilizer in the same way and using the same equipment as the spreading of animal manures and slurries. The most suitable methods of application are the same as those used to apply raw, untreated slurry. The equipment used should minimize the surface area exposed to air and ensure rapid incorporation of digestate into the soil. For these reasons, digestate is best applied with trailing hoses, trailing shoes or by injection into the topsoil. Spreading digestate by splash plate is banned in many countries as it causes air pollution and losses of valuable nutrients. Digestate has a declared content of nutrients and can be therefore completely integrated in the fertilization plan of the farm. Due to its higher homogeneity and flow properties, digestate penetrates soil faster than untreated animal slurries (Al Seadi *et al.*, 2008). The application of digestate as fertilizer involves risks of nitrogen losses through ammonia emissions and nitrate leaching. In order to minimize these risks, the following simple rules of good agricultural practice should be applied.

- Digestate should be only applied at the start of vegetative plant growth (i.e. spring).
- Optimum weather conditions for the application of digestate are high humidity but not excessive rain and no wind.
- Dry, sunny and windy weather increases evaporation and reduces nitrogen efficiency considerably.
- Moderate stirring of digestate before application is recommended.
- Only cooled digestate from the post-storage tank should be applied.
- Dragging pipes, dragging hoses or direct injection into soil should be used for digestate application, never broad spreading (splash plate spreading).
- If digestate is applied to the surface of soil it should be immediately incorporated into the soil.

For economic efficiency, the fields where digestate is applied should be located close to the biogas plant, to avoid increased transport costs. When digestate has to be transported for longer distances, volume reduction through solid–liquid separation can be considered. As the liquid and the solid fraction of digestate are used separately, different characteristics of the products have to be considered (Fuchs and Drosig, 2010). Both fractions contain the macronutrients nitrogen, phosphorus and potassium. The liquid fraction contains higher amounts of potassium and nitrogen whereas the solid fraction contains fibrous material and higher amounts of phosphorus. The simplest way of using these fractions is for the solid fraction to be composted and used as soil improver, while the liquid fraction can be

applied as nitrogen-rich fertilizer or further processed and sold as concentrated liquid fertilizer. The economics of such processes have to be considered in advance.

For agricultural biogas plants that digest energy crops and/or manure and vegetal residues from crop production, hygiene and contamination aspects are usually not a problem for use of digestate as fertilizer. Pathogen inactivation is important if the produced digestate is also used as fertilizer by other farmers. In centralized co-digestion plants that co-digest manure from several farms with various types of wastes and residues, strict hygiene and other quality assurance measures must be taken in order that no pathogens are transmitted between farms and the produced digestate is not polluted by xenobiotic compounds. The tankers used to transport feedstock to the biogas plant must be cleaned and disinfected before loading with digestate for subsequent delivery to the farm, using standard procedures for cleaning biomass transport vehicles. The tanker will service one farm at a time and the same disinfection procedures must be applied before servicing the next farm (Al Seadi and Lukehurst, 2012). Depending on the local nutrient situation, digestate can be sold or given for free to crop farmers. The biogas plant operator rarely pays a tipping fee when digestate is taken by crop farmers.

Digestate as soil improver

The separated solid fraction of the digestate can be further processed by composting. The resulting compost can be used as a multifunctional soil improver in agriculture and horticulture or for topsoil production. The application of compost from digestate has the same effect on soil as any high-quality compost, improving soil quality, bringing valuable microorganisms into the soil and improving the water retention capacity and the pH buffer capacity of the soil. Digestate contains important amounts of phosphorus and potassium, covering the crop requirement of such nutrients in many cases. As with all soil improvers, the quality of the composted digestate used as soil improver is defined by parameters such as dry matter content, organic matter content, pH, nutrient content, particle size and bulk density.

12.4.2 Re-utilization of digestate on site

Re-utilization of the liquid fraction

Digestate fractions from solid–liquid separation are frequently re-fed to the AD reactor. This is common practice for dry digestion processes, either continuous or batch, where the liquid fraction is recirculated. In continuous dry digestion processes, the feedstock material (e.g. silage) is mixed with the liquid digestate fraction and digested. This is often done in a plug-flow

digester. In batch dry digestion processes, the liquid fraction, which is also called percolate, is used to recirculate microorganisms and nutrients in the process. In wet digestion (wet fermentation), a share of the liquid fraction can be reused as mashing liquid for the feedstock. This is the case in agricultural AD plants digesting very little or no manure, where the liquid fraction can be used to achieve the desired dry matter content (usually around 10%) of the feedstock mixture. In waste treatment processes, the liquid fraction can be used to solubilize the organic wastes in, for example, pulpers.

Re-utilization of the solid fraction

The solid fraction of digestate can be mixed with the other feedstocks and re-fed to the digester in order to enhance the dry matter content, as is often the case with pig slurries. There are also practices where the solid fraction of digestate is treated on site by fungi or other treatments, with the aim of making the recalcitrant matter in the solid fraction more available to anaerobic microorganisms and thereby increasing methane. The separated fibers can be used in storage bunkers to cover silage, such as corn or grass silage, replacing the foil cover which reduces decomposition. The fibers are re-fed to the digester together with the silage used as AD feedstock.

A recently investigated method for seasonal AD plants is the storage of microorganisms in digestate pellets, used to inoculate the new AD processes of the next season. Speetzen *et al.* (2011) investigated storage opportunities for microorganisms from biogas plants treating wastewater from potato and sugar beet industries. The production and AD of these wastewaters is seasonal, and thus digestate pellets are used to inoculate the new process and shorten the start-up time (with lower methane production) of the AD plants, required by the adaptation phase of the microorganisms. Speetzen *et al.* (2011) indicate that the pellets can be stored at 4°C for a year, at low cost and without problems. However, for this application, only a very small fraction of the digestate will be recirculated and it will be a niche application to seasonal plants only.

12.4.3 Digestate as an energy carrier

Whenever possible, digestate should be used as fertilizer or soil improver, as its application adds nutrients and organic matter to the soil, with positive impacts on overall fertility and carbon storage. Exceptions are situations when the quality of digestate is not suitable for use as fertilizer (e.g. high concentrations of chemical pollutants), when such utilization is prohibited by national legislation, as is often the case for digestate from AD plants treating sewage sludge from wastewater treatment plants or unsorted municipal solid waste, or when use as fertilizer is not feasible, as is the case

in areas with an excess of nutrients. In such situations, the use of digestate for energy purposes, such as co-combustion for power generation, can be a option. Further energetic use will normally involve additional treatment such as fiber separation, drying and even pelletizing. The high ash, sulfur and nitrogen content of digestate will necessitate emission control.

12.4.4 Other uses of digestate

An uncommon yet increasing use of the solid fraction of digestate is as bedding material in animal breeding stables, substituting for straw. Research on construction materials from dried manure fibers of AD-processed animal manure carried out by Winandy and Cai (2008) and Spelter *et al.* (2008) showed that the solid fraction of digestate can also be used to make low-grade building products such as fiberboards or composite materials. According to Rigby and Smith (2011), it would be possible to produce medium density fiberboards (MDF) and wood–plastic composites (WPC) from digestate resulting from food waste. The fibers of this digestate are dried and blended with liquid resin and then pressed and formed into panels, which is the same process as for treating wood to produce panels. Another potential opportunity to use solid digestate is as raw material for bio-pesticide production, specifically for the cultivation of *Bacillus thuringiensis*, which is needed for the production of many bio-pesticides (Rigby and Smith, 2011). In this case, the composition and the C/N ratio of digestate have to be suitable and detailed investigation of the suitability of digestate as a growth medium is required. A niche product for the use of digestate may be the preparation of activated carbons by phosphoric acid activation, as investigated by Yuan *et al.* (2010).

Digestate can be also used for vermiculture, producing high-quality earthworm compost. Surplus earthworms can be then fed to chickens. In countries such as China, digestate has been used as an additive to animal feed for pig, chicken, fish and shrimp production; this option is limited by national legislation and public acceptance.

12.5 Conclusion

Increasingly strict environmental legislation in most countries is aimed at the avoidance of pollution of all kinds and losses of biodiversity, as well as the prevention of any potential toxic effects and health risks for living organisms. Producing digestate of high quality is part of the overall demand for quality in today's society and is an integral part of biogas technologies, providing more than just renewable energy. Besides renewable energy, biogas from AD has the potential to deliver environmentally sound and veterinary-safe solutions for the treatment of animal manure and suitable

organic wastes. Use of digestate as biofertilizer contributes to resource preservation through the recycling of organic matter and nutrients, such as phosphorus, a highly limited fossil resource on our planet. As digestate is often utilized as fertilizer for crops dedicated to food and feed production, its quality directly impacts on food quality and food safety. The demand for quality necessarily implies the existence of a unified approach and a system of quality parameters. In the case of digestate, legal frameworks for the implementation of quality standards contribute to the development of a sound and stable market for this product, raising confidence in its quality and suitability. The quality of digestate can be further improved by conditioning through digestate processing. Although digestate processing means additional investments, operation and maintenance costs, the possibility of improving digestate quality, transportability and marketability are important incentives. Digestate is a good product, suitable for many kinds of utilizations. Recycling as biofertilizer is by far the most sustainable utilization of digestate. Quality-assured digestate, applied as fertilizer in line with the best agricultural practices, allows achievement of long-term benefits that outweigh the potential risks (Al Seadi and Lukehurst, 2012).

12.6 Sources of further information and advice

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Abstract: The anaerobic digestion process involves the breakdown of organic matter to produce biogas, a mixture of CH₄ and CO₂ gases. During this process, nutrients are transformed, volatile fatty acids are consumed and pathogens reduced, leading to potential environmental and agronomic benefits associated with the land application of digestate. An extensive examination of the effects of land application of digestate on NH₃ and N₂O emissions, odour emissions, crop yield and migration of NO₃⁻-N and bacteria to drainage tiles is presented. Experimental field data collected by the authors supporting these environmental and agronomic impacts are referenced throughout the chapter.

Key words: digestate, land application, GHG emissions, odours, ammonia volatilization, nitrate leaching, pathogen migration.

13.1 Introduction

The potential of producing electricity and generating an additional financial stream has driven a growing interest in the adoption of on-farm anaerobic digesters. However, the environmental benefits associated with manure anaerobic digestion, which include reduced greenhouse gas (GHG) emissions, reduced odours, improved fertilizer nutrients and reduced pathogens, can also help advance the uptake of farm digester technologies.

The anaerobic digestion process involves the breakdown of biodegradable organic matter by a microbial population to produce a mixture of CH₄ and CO₂ gases. This biogas can subsequently be used to produce both electricity and heat. The capture and combustion of methane reduces its emission to

the atmosphere, thereby reducing GHG emissions (Venczel and Powers, 2010). The collection and use of CH_4 in the production of electricity and heat has been estimated by Sommer *et al.* (2004) to reduce CH_4 emissions by up to 85–90% when compared with the conventional method of storing manure in uncovered reservoirs. During the anaerobic digestion process, manure nutrients are also transformed: organic N into NH_4^+-N and organic P into $\text{PO}_4^{3-}-\text{P}$ (Burke, 2001). Collins *et al.* (2010) suggest reduced N_2O emissions could be expected after the land application of digested manures due to lower C to N ratios (C:N), resulting in less available organic C needed for denitrification. Pathogens are also reduced during the anaerobic digestion process. Crolla and Kinsley (2008) and Monreal *et al.* (2012) demonstrated a 1 to 2 log reduction in a suite of pathogen indicators (*E. coli*, *Salmonella*, *C. perfringens* and Enterococci) after the anaerobic digestion of liquid dairy manure.

This chapter discusses the potential environmental impacts associated with the land application of digestate on agricultural fields, when compared with raw manure and inorganic fertilizer. The transformation of nutrients and pathogen die-off during the digestion process is discussed. An extensive examination of the effects of land application of digestate on NH_3 and N_2O emissions, odour emissions, crop yield and migration of NO_3^--N and bacteria to drainage tiles is presented. Experimental field data collected by the authors supporting the impacts associated with the land application of digestate are referenced throughout the chapter.

Anaerobic digestion is commonly used in various applications, including the digestion of agri-food residues, municipal sludge and industrial wastes. This chapter, however, will be exclusively dedicated to the discussion of agriculture-based digestates.

13.2 Overview of substrates and land application of digestate

13.2.1 Characteristics of manures and co-substrates

During anaerobic digestion, the organic matter in feedstocks is transformed into biogas and digestate. The feedstocks typically used in agriculture-based digesters include manures, agriculture crops, agri-food industry wastes and the organic fraction of household wastes. Manure itself has a relatively low biogas yield; however, when co-digested with organic-rich substrates, biogas production is significantly increased. The addition of co-substrates to manure can also improve the C:N ratio, which results in a stable digestion process and good digestate fertilizer quality (Braun and Wellinger, 2003). Table 13.1 describes the characteristics of selected substrates suitable for anaerobic digestion.

Table 13.1 Composition of selected substrates suitable for digestion

Substrate	Total solids (g/kg)	Volatile solids (g/kg)	Total N (g/kg)	Ammonium nitrogen (NH ₄ ⁺ -N) (g/kg)	Total P (g/kg)
Animal manures					
Liquid dairy manure	110 ± 23	90 ± 21	3.9 ± 0.9	1.7 ± 0.8	0.7 ± 0.3
Poultry broiler manure	452 ± 30	256 ± 25	20.1 ± 3.1	12.5 ± 2.3	1.2 ± 0.4
Swine manure slurry ^a	37	N/A ^b	4.0	2.7	1.3
Horse dung	230 ± 28	190 ± 33	1.1 ± 0.3	0.7 ± 0.1	0.4 ± 0.1
Crops					
Corn silage ^c	472 ± 10	445 ± 11	1.8 ± 0.3	0.9 ± 0.1	0.2 ± 0.1
Switchgrass ^c	461 ± 17	435 ± 14	4.3 ± 1.4	N/A	0.4 ± 0.1
Agri-food industry wastes					
Waste grease	228 ± 43	202 ± 45	1.4 ± 0.8	0.3 ± 0.1	0.2 ± 0.1
Grocery food waste	169 ± 35	138 ± 54	1.7 ± 0.7	1.3 ± 0.4	0.3 ± 0.2
Corn thin stillage (ethanol brewery waste)	108 ± 22	92 ± 19	1.9 ± 0.4	0.1 ± 0.0	0.9 ± 0.5

^a OMAFRA (2011).^b Not available.^c Total N, NH₄⁺-N and total P concentrations based on air-dried mass of substrate.

Note: Mean concentrations reported on wet mass basis ± standard deviation unless stated otherwise.

Source: Data collected by University of Guelph.

Animals are typically inefficient at digesting nutrients from dietary feed and excrete high proportions of these nutrients, resulting in animal manures with relatively high proportions of N and P (Van Horn *et al.*, 1996; Lukehurst *et al.*, 2010). The composition of animal manures is not only affected by the digestive system (ruminant vs. omnivore) and age of the animal but also by farm practices (bedding type, washwater volume, manure storage, etc.). Table 13.1 demonstrates that the N composition in solid manure (e.g. poultry broiler) can be as much as five times greater than liquid manure (e.g. liquid dairy). The variability in manure nutrient composition has a significant influence on the digestion process, thereby influencing the nutrient content in the digestate.

Co-substrates, which can include crops or agri-food industry wastes, are added to manure to enhance biogas yields. These co-substrates typically have much higher organic matter content, measured as volatile solids (VS), with respect to nutrients. The addition of these co-substrates to manure drives the C:N ratios of the mixture to optimum digestion values ranging between 20:1 and 30:1 (Burke, 2001; Gerardi, 2003; Sakar *et al.*, 2009). Some co-substrates used in manure digestion may introduce heavy metals or other contaminants that are not biodegraded during digestion. Because these

Table 13.2 Mean nutrient concentrations from four farm digesters co-digesting dairy manure and waste grease

	Total solids (g/kg)	Total N (g/kg)	NH ₄ ⁺ -N (g/kg)	Total P (g/kg)	PO ₄ ³⁻ -P (g/kg)
Feedstock mixture (dairy manure + grease)	131 ± 22	3.5 ± 0.6	1.4 ± 0.3	0.5 ± 0.1	0.3 ± 0.0
Digestate	57 ± 5	3.6 ± 0.4	1.9 ± 0.5	0.5 ± 0.0	0.4 ± 0.1
Change	-56.4%	None	+35.7%	None	+ 33.3%

Note: Mean concentrations reported on wet mass basis ± standard deviation.

Source: Data collected by University of Guelph.

contaminants are present in the digestate, local regulations stipulating the legal limits for the land application of the contaminants must be respected.

13.2.2 Transformation of nutrients and pathogen die-off during digestion

During anaerobic digestion, organic matter is degraded, with organic C converted to CH₄ and CO₂. As well, nutrients in organic matter are transformed into their inorganic forms; for example, organic N is converted to NH₄⁺-N and organic P is converted to PO₄³⁻-P (Gerardi, 2003). It should be noted the total nutrient content remains the same during digestion; only their respective forms are changed. Table 13.2 summarizes the mean change in digestate characteristics from four farm mesophilic (40°C) digesters in Ontario, Canada, co-digesting liquid dairy manure with waste grease.

The increased concentration of inorganic nutrients, particularly NH₄⁺-N, can contribute to increased crop yields as mineral nutrients are readily available for crop uptake soon after land application. However, if the pH of the digestate is high enough (pH > 7.2) and climate conditions are suitable, increased quantities of unionized ammonia (NH₃) may volatilize upon surface application. The impacts associated with the land application of digestate compared to raw manure on crop productivity and on the environment are addressed later in the chapter.

The die-off of pathogens in anaerobic digesters has always been of importance in the treatment of sewage sludge and is now of greater interest in the treatment of agriculture residues, as it may lead to reduced pathogen migration to soil subsurface drainage tiles. Pathogens can be inactivated during exposure to heat above their optimum growth temperature. The period of exposure is dependent on the temperature and on the species of the organism. A lab study conducted by Kumar *et al.* (1999) demonstrated a 3-log reduction in *E. coli* and *Salmonella* after 10 days of batch digestion of

Table 13.3 Log mean bacteria concentrations in four farm digesters co-digesting dairy manure and waste grease

	<i>E. coli</i> (log CFU/100 ml)	<i>Salmonella</i> (log CFU/100 ml)	Enterococci (log CFU/100 ml)
Feedstock mixture (dairy manure + grease)	7.5 ± 0.6	5.6 ± 0.8	7.3 ± 0.4
Digestate	5.0 ± 0.9	4.3 ± 0.5	5.0 ± 0.6
Log reduction	2.5	1.3	2.3

Note: Log mean concentration reported on wet mass basis ± log standard deviation.

Source: Data collected by University of Guelph.

cattle manure at 35°C, whereas a 5-log reduction in *Shigella* was observed under the same conditions. Harikishan and Sung (2003) presented similar findings with 5-log and 3-log reductions in fecal coliforms and *Salmonella* respectively during temperature-phased anaerobic digestion (TPAD) of dairy manure. The two-stage TPAD system consists of an acid-producing thermophilic (55°C) stage followed by a methane-producing mesophilic (35°C) stage of digestion. The authors suggested pathogen destruction was not only attributed to the high operating temperatures but also to the accumulating volatile fatty acids (VFAs) in the first stage. Table 13.3 presents the log mean reductions in *E. coli*, *Salmonella* and Enterococci bacteria in four farm mesophilic (40°C) digesters in Ontario, Canada.

Smith *et al.* (2005) suggest a 2-log reduction in *E. coli* is perhaps the highest level of bacterial inactivation that can be anticipated from a mesophilic digester. This finding is confirmed by Wright *et al.* (2004) as well as the bacterial log reductions presented in Table 13.3. It was also suggested by Smith *et al.* (2005) that efficient mixing in the digester and organic matter stabilization (long retention times) were also important factors for bacterial inactivation in mesophilic digesters.

13.2.3 Methods of land application

Raw manure or digestate can be land applied using various types of equipment. Solid digestate that is greater than 18% total solids (TS) can be surface broadcast. Digestate that is less than 18% TS, but more typically 12% TS, can either be surface applied or subsurface injected (OMAFRA, 2005; AARD, 2007). Surface applied digestate should be soil incorporated to avoid odour emissions and loss of nutrients through runoff and volatilization. Figure 13.1 shows the surface application of liquid digestate at University of Guelph experimental plots using a tanker spreader with splash plate (a) followed by soil incorporation using a cultivator (b). The expected amount of NH₃ losses within the first 24 hours after surface



(a)



(b)

13.1 Surface application of digestate at University of Guelph, Campus d' Alfred experimental plots. (a) Tanker spreader with splash plate. (b) Cultivator for digestate incorporation within 24 hours of application.

application of raw manure can range from 10% (cool and wet conditions) to 50% (warm and dry conditions) (AARD, 2007). These losses may be even higher in digestates due to their higher NH_4^+ -N concentrations. Therefore, incorporating digestates either immediately or within a few hours of application is essential to minimizing nutrient losses. Sommer and

Table 13.4 Components of a typical NMP

NMP component	Description
Site assessment	Includes description of fields (area, length and grade of slopes, minimum separation distances to sensitive areas), soil type and soil tests
Manure/digestate assessment ^a	Includes description of animal feed, manure/digestate volumes, manure/digestate storage facilities and analysis of manure/digestate nutrient content
Nutrient land application plan ^a	Includes information on manure/digestate application and incorporation methods, calibration of equipment, crop rotations, planned seeding and harvesting, application rates for manure/digestate (based on N and P needs of crop) and timing of application and incorporation
Land management plan	Includes information on practices and controls that will reduce nutrient runoff (e.g. buffer strips, controlled erosion)
Reporting	Includes procedure for keeping detailed and organized records

^a These components also apply to inorganic fertilizers, if being used on the farm. Source: OMAFRA (2005), AARD (2007).

Hutchings (2001) report NH_3 loss rates are highest in the first few hours following application. Injection systems will reduce the exposure of digestate to air, thereby significantly reducing NH_3 volatilization and potential odour nuisances (Sommer and Hutchings, 2001; AARD, 2007; Ndegwa *et al.*, 2008).

13.2.4 Nutrient management planning

The land application of digestate, as is the case for manure or any other crop fertilizer, must be considered in a nutrient management plan (NMP). A NMP is designed to develop a series of best management practices that will manage nutrients used for crop production in an environmentally sound manner. Table 13.4 describes the essential elements of a NMP. The individual components of a NMP will vary among jurisdictions.

NMPs should be revised routinely but particularly when changes to farm management practices are made. Regulations in individual jurisdictions will detail the appropriate procedures in dealing with manure, nutrient and soil management. Unless otherwise stipulated by the local governing body, these regulations will also apply to the land application of digestate.

13.3 Field experience of land application and associated environmental impacts

13.3.1 Background on nitrogen transformations in soils

Plants require 13 mineral nutrient elements for growth. Each of these nutrients is critical for plants to complete their life cycle. Macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulphur) are required by plants in the largest amounts, while micronutrients (iron, copper, manganese, zinc, boron, molybdenum and chlorine) are required in relatively smaller amounts. Nitrogen is one of the most important nutrients for plant growth, as N is an essential component of chlorophyll molecules, amino acids and enzymes (Olson and Kurtz, 1982). Plants can uptake N in the inorganic forms of NH_4^+ -N and NO_3^- -N. The organic nitrogen in animal manures and plant residues must be degraded in the soil prior to becoming available for plant growth. Proteins are converted by bacteria to NH_4^+ -N through mineralization, also referred to as ammonification, and other soil microorganisms oxidize NH_4^+ -N to NO_3^- -N via nitrification. Finally, to complete the nitrogen cycle, anaerobic soil bacteria reduce NO_3^- -N to N_2 and N_2O gases through a process known as denitrification.

Nitrogen mineralization is a function of the C:N ratio. When C:N ratios are low (less than 20:1) microorganisms will rapidly mineralize organic N and release inorganic forms, whereas higher C:N ratios result in a slow mineralization process (Jansson and Persson, 1982; Bengtsson *et al.*, 2003; Khalil *et al.*, 2005). During the anaerobic digestion process, organic matter is broken down to convert C to CH_4 and CO_2 , resulting in digested substrates having low C:N ratios. Digestate samples were taken at five on-farm digesters in Ontario, Canada, over a period of six months, and the C:N ratios ranged between 5.6 and 7.8:1. The low C:N ratio of digestate would suggest nitrogen mineralization can be enhanced when soil fertility is amended with digested materials, thereby increasing the N availability for crop uptake.

The transformation of N in soils is largely influenced by soil temperature and soil moisture. Nitrification is essentially inactive at temperatures less than 4°C (Schmidt, 1982). A study conducted by Stark (1996) found maximum nitrification rates to occur at temperatures between 30 and 35°C, while Grundmann *et al.* (1995) found optimal nitrification rates at temperatures between 20 and 25°C. Schmidt (1982) reported that optimum temperatures for nitrification vary among soils: 20–25°C for soils in northwestern USA and 30–40°C for soils in southwestern USA. Nitrification in soils that are wet beyond their field capacity will be substantially reduced, as nitrifying bacteria are sensitive to moisture stress that reduces adequate soil aeration (Schmidt, 1982; Fierer and Schimel, 2002). Maag and Vinther (1996) investigated the effects of temperature on

denitrification in a lab study with various soil types and found that denitrification increased with temperature under high soil water content. These findings were corroborated by Griffin *et al.* (2002) who found that high soil water content (e.g. 70–100% water-filled pore space) favours denitrification. Nitrogen transformations in soils will be highly dependent on seasonal temperatures and soil moisture conditions with particular differences observed in fall compared with spring land application of manure.

The following sections elaborate on how digestate composition, climatic conditions and N transformations influence environmental impacts of land applied digestate. Gas and odour emissions, crop yield and migration of nitrates and pathogens to subsurface tile drains will be addressed.

13.3.2 NH₃ and N₂O emissions

The land application of manure, digestate and inorganic fertilizers induce NH₃ volatilization and N₂O emissions. Ammonia volatilization is of particular concern just after land application and can result in a considerable loss of the applied N, as described by Chantigny *et al.* (2007) and AARD (2007). The volatility of NH₃ is dependent not only on climatic conditions, with warm and dry atmospheric conditions favouring volatilization, but also on pH and soil infiltration (Sommer and Hutchings, 2001). When pH increases above 7.2, the presence of unionized NH₃ in solution becomes more favourable (Gerardi, 2003), ultimately increasing NH₃ volatility. Anaerobic digestion increases pH and the carbonate content in the digestate, thereby suggesting land application of digestate could increase NH₃ emissions (Chantigny *et al.*, 2004). However, lower NH₃ emissions could be anticipated with digestate as its inherently lower solids content (viscosity) allows increased infiltration of digestate into the soil (Sommer and Hutchings, 2001; Chantigny *et al.*, 2007).

Several studies comparing NH₃ emissions of raw manure and digestate have been conducted. Chantigny *et al.* (2007) investigated the land application of raw and digested liquid swine manure and determined that the three-year mean NH₃ emissions from the plots receiving digestate were 20% lower than raw manure plots. The authors attributed the lower NH₃ emissions in the digestate plots to increased soil infiltration due to the lower solids content (viscosity) of the digestate. However, it should be noted that in a previous study conducted by Chantigny *et al.* (2004), no differences were observed in NH₃ emissions between plots treated with raw manure and digestate. Rubaek *et al.* (1996) also found no NH₃ emission differences between raw manure and digestate plots, but did report higher NH₃ emissions when raw manure was applied to dry, hydrophobic, bare soils.

High NH₄⁺-N concentrations and easily degradable organic C of manure

can enhance denitrification in soils and increase N_2O emissions (Wulf *et al.*, 2002; Chantigny *et al.*, 2010), with significant N_2O emissions following land application of liquid animal manures often observed (Chantigny *et al.*, 2007). Alternatively, although digestate typically has a higher concentration of NH_4^+-N , Vallejo *et al.* (2006) suggested that the easily degradable C in manure would be decomposed during digestion and the remaining more stable C would be less likely to stimulate denitrification, resulting in lower N_2O emissions. Chantigny *et al.* (2010) observed denitrification to be in fact N-limited in clay soils and C-limited in loam soils, suggesting a high NH_4^+-N content, but low degradable C of digestate could still stimulate denitrification in clay soils. As discussed earlier in the chapter, nitrification and denitrification of soils is highly dependent on climatic conditions. Rochette *et al.* (2004) reported that manure slurries with high NH_4^+-N concentrations were easily nitrified in spring when soils were well aerated and warm, whereas, for fall manure application, wet and cold conditions limited net nitrification, thereby limiting denitrification and N_2O emissions.

A few studies have been conducted to compare N_2O emissions from the land application of raw manure and digestate. Vallejo *et al.* (2006) studied the land application of raw swine manure and digestate on clay loam soils and determined N_2O emissions from digestate plots to be 48% lower than those treated with raw swine manure. In a study conducted by Chantigny *et al.* (2007) lower N_2O emissions were consistently observed over 3 years from both loam and sandy loam plots that received digested compared to raw swine manure. A possible explanations could be that some compounds in digestate have depressive effects on soil nitrifying bacteria, thereby reducing the supply of nitrate compounds needed for denitrification (Nyberg *et al.*, 2004) or the C in digestate is not easily degradable and less likely to stimulate denitrification (Vallejo *et al.*, 2006). Amon *et al.* (2006) also reported lower N_2O emissions from plots receiving digested dairy manure. However, Wulf *et al.* (2002) reported similar N_2O emissions among digestate and raw dairy manure treated arable soil plots but higher N_2O emissions when digestate was applied to grassland soils.

A study conducted in Ontario, Canada, by Agriculture and Agri-Food Canada (AAFC) and University of Guelph investigated NH_3 and N_2O emissions from the land application of raw liquid dairy manure and digestate on clay-loam soils. Nitrous oxide emissions were measured using the flux-gradient technique equipped with a closed-path single optical pass tunable diode laser (TGA-100, Campbell Scientific, Logan) (Fig. 13.2), as described by Pattey *et al.* (2006), while NH_3 volatilization was measured by the relaxed eddy accumulation technique using denuder tubes (Zhu *et al.*, 2000). Nitrous oxide and NH_3 emission factors for both the fall and spring land application trials are summarized in Table 13.5. When raw manure and digestate were surface broadcast in fall 2005, the N_2O emission factor was



13.2 N₂O and NH₃ emission measurements being taken by AAFC research group during land application trials for raw liquid dairy manure and digestate.

Table 13.5 N₂O and NH₃ emission factors following land application of raw dairy manure and digestate

	Digestate (fall application)	Raw manure (fall application)	Digestate (spring application)	Raw manure (spring application)
NH ₃ emission factor (kg NH ₃ -N/kg NH ₄ ⁺ -N _{applied})	0.40	0.23	0.25	0.21
N ₂ O emission factor (kg N ₂ O-N/kg N _{applied})	0.035	0.029	0.021	0.025

Source: Data collected by AAFC.

only slightly higher (1.2 times higher) for the field treated with digestate. However, the NH₃ emission factor was much higher (1.7 times higher) for the digestate-treated field. In spring 2007, the land application of raw manure and digestate resulted in only slight differences between the respective NH₃ and N₂O emissions factors. For both experiments, most of the NH₃ volatilization took place within 6 hours of the land application of the dairy manures, as was observed during a previous field experiment where dairy slurry was applied in September (Beuning *et al.*, 2008).

The number of studies investigating NH₃ and N₂O emissions from digestate are limited and further studies are needed to better understand gas

emissions under various climatic and soil conditions, thereby helping to refine NH_3 volatilization models such as AGRIN (Beuning *et al.*, 2008).

13.3.3 Odour emissions

As the urban fringe encroaches onto agricultural lands and livestock operations intensify, there are growing complaints concerning odours associated with agricultural activities. Odours from farms can be generated from barns that house animals and feed, the manure storage structure and the land application of manure (Powers, 1999). The odorous compounds, which are generated by numerous bacterial species, include volatile fatty acids (VFAs), aromatic compounds (e.g. phenols), nitrogen-containing compounds (e.g. NH_3) and sulphur-containing compounds (e.g. H_2S) (Rappert and Müller, 2005).

Odorous compounds have been shown to be reduced during the anaerobic digestion process. Powers *et al.* (1999) demonstrated more than 99% reduction in total VFAs and 60% reduction in phenols during a lab-scale digestion of dairy manure. The authors stated that, although NH_3 concentrations increased in the digestate, NH_3 was not a major contributor to odour. Crolla and Kinsley (2008) also reported significantly lower VFA concentrations in the digestate from two farm-scale mesophilic (40°C) digesters (in Ontario, Canada) co-digesting dairy manure and waste grease, with average reductions in total VFAs greater than 95%.

A quantitative study was conducted by the University of Guelph (Ontario, Canada) and Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) to determine whether the decreased odour compounds in digestate would translate into reduced odours during land application. Lab simulation studies were conducted to determine surface odour concentrations expressed as odour units per cubic metre of applied substrate (OU/m^3). Standard flux chamber and wind tunnel protocols and odour flux measurements were applied. The odour studies were conducted using raw dairy manure and digestate from the same two farm digesters studied by Crolla and Kinsley (2008). Table 13.6 summarizes the odour measurements taken using flux chamber and wind tunnel methods. Odour emissions were significantly lower with the application of digestate, which demonstrates that anaerobic digestion is an important tool in reducing odours.

13.3.4 Crop yields

Digestate typically has higher $\text{NH}_4^+ - \text{N}$ concentrations than raw manure (as illustrated in Table 13.2) and it is anticipated this readily available form of N can result in increased crop productivity. However, the potential loss of N from NH_3 volatilization during land application should be considered. As

Table 13.6 Odour concentrations for raw manure and digestate using the flux chamber and wind tunnel methods

Manure type	Flux chamber average odour concentration (OU/m ³)	Wind tunnel average odour concentration (OU/m ³)
Digester 1		
Raw manure	2625	898
Digestate	604	111
Digester 2		
Raw manure	2429	656
Digestate	762	441

Source: Data collected by University of Guelph and OMAFRA.

discussed earlier, the increased pH and carbonate content in digestate can stimulate NH₃ volatilization; however, this can be counterbalanced with reduced NH₃ volatility due to lower digestate viscosity, which increases soil infiltration (Gerardi, 2003; Chantigny *et al.*, 2004). A study conducted by Chantigny *et al.* (2007) demonstrated increased forage dry matter (DM) yields of timothy when comparing digestate to raw manure application. A 0.2 ton DM/ha and 0.6 ton DM/ha respective yield increase was observed in loam and sandy loam plots following surface-applied digested liquid swine manure, compared with plots treated with raw slurry. Measured N uptake in the timothy crop was also higher in the digested manure plots. The authors suggested the difference in crop yields was partly due to N loss from the increased volatilization of NH₃ observed in the plots treated with raw swine manure. This increased NH₃ loss can be attributed to the slower infiltration of raw swine manure due to its higher viscosity. In this study the manure types were not soil incorporated after application. A further study conducted by Chantigny *et al.* (2008) demonstrated no significant difference in corn grain yields between plots treated with raw and digested liquid swine manure; however, unlike the 2007 study, the raw and digested manures were surface applied and immediately incorporated to minimize NH₃ volatilization.

Field trials were conducted at the University of Guelph in which plots were land applied with either raw dairy manure or digestate. Each of the 400 m² sandy loam plots received an application rate of 140 kg N/ha and were planted with grain corn. Table 13.7 summarizes the seed corn yields over two years of trials. Fig. 13.3 shows the corn plants at the experimental plots. The study demonstrated an average 19% increase in corn yield for plots treated with digestate over two years.

Schröder *et al.* (2007) investigated the effects of digested cow manure on cut grassland and reported a 14% higher N fertilizer replacement value (N needed for plants) in the same year of application when compared with raw cow manure. Whereas in the subsequent four years when no treatments were

Table 13.7 Seed corn yields from sandy loam plots having received raw and digested dairy manure treatments

Year	Corn yield (dry ton/ha)	
	Plots treated with raw manure	Plots treated with digestate
2009	4.3	5.2
2010	4.1	4.7
Mean	4.2	5.0

Note: Yields based on dry mass.

Source: Data collected by University of Guelph.



13.3 Corn plots having received raw manure, digestate and inorganic fertilizer as soil amendments at University of Guelph, Campus d' Alfred experimental plots.

applied, the plots that had received digested manure demonstrated relatively small residual N effects, while residual N was higher in the plots that had received raw manure. Increased crop yields with digestate treatments can be explained by higher $\text{NH}_4^+ - \text{N}$ concentrations available for plant uptake; however, the lower C:N ratio of digestate, compared with raw manure, results in greater N availability in the soil that can induce N mineralization (Chantigny *et al.*, 2007).

The effects of digestate application on crop yields have demonstrated variable results, from no effect to significant increases in crop yield. Further field studies are needed to better understand long-term yield response under various cropping, climatic and soil conditions.

13.3.5 $\text{NO}_3^- - \text{N}$ leaching to drainage tiles

Nutrient management planning involves amending soils with sufficient nutrients to satisfy the needs of crops while minimizing nutrient losses that can lead to negative environmental impacts. As previously discussed, NH_3 volatilization represents a significant route for N loss during and immediately after land application of manure or digestate. N losses are

also attributed to NH_4^+ -N and NO_3^- -N via surface runoff and soil leaching. Due to its high solubility in water, NO_3^- -N is the major N species lost by leaching (Goss *et al.*, 2001). Denitrification further influences N losses with the production of gaseous N_2O and N_2 .

Nitrogen loss through NO_3^- leaching is an important water quality issue, where high NO_3^- -N concentrations in subsurface waters could lead to contaminated drinking water sources and have possible negative effects on human health (Goss *et al.*, 2001; Dinnes *et al.*, 2002; Stoddard *et al.*, 2005). Leaching of NO_3^- -N is dependent on the type of soil amendment and how its composition affects N transformations in the soil. Studies conducted by Jokela (1992) and Stoddard *et al.* (2005) demonstrated lower NO_3^- -N concentrations in leachate from plots that received dairy manure compared with those treated with inorganic fertilizer. In both studies, average NO_3^- -N concentrations in leachate were typically less than 13 mg/l. The authors indicated the higher organic C from manure may have increased denitrification or N mineralization was in equilibrium with plant N uptake, resulting in less NO_3^- -N production in soils. However, by the end of the Stoddard *et al.* (2005) study, the plots having received manure had higher leachate NO_3^- -N concentrations than the plots treated with inorganic fertilizer, suggesting that long-term manure use can result in a delayed NO_3^- -N leaching potential due to continued N mineralization from soil accumulated manure organic matter. Jemison and Fox (1994) demonstrated the effects of growing season on NO_3^- -N leachate concentrations and found that, during the non-growing months, NO_3^- -N concentrations increased in plots that received dairy manure compared with inorganic fertilizer plots. The authors suggested N mineralization in the manured plots led to NO_3^- -N production when no plants were available for N uptake. Nitrate leaching is also affected by rainfall and land application practices. Powell *et al.* (2011) reported mean NO_3^- -N leachate concentrations were highest with increased rainfall with negligible concentrations observed at very low rain events. The authors also reported that when liquid dairy manure was surface applied and not incorporated, NH_3 losses increased, which in turn resulted in decreased N availability for leaching. The study demonstrated no differences in NO_3^- -N leaching between surface application (no incorporation) and subsurface injection.

Multiple year field studies were conducted at the University of Guelph Campus d'Alfred (Ontario, Canada) to investigate the effects of land-applied raw dairy manure and digestate on NO_3^- -N leaching to drainage tiles (1 m below soil surface). Each of the 1500 m² Bearbrook clay plots received an application rate of 140 kg N/ha and were planted with grain corn. Table 13.8 summarizes the mean NO_3^- -N concentrations in the tile drains. Figure 13.4 demonstrates the sampling setup for the collection of tile



(a)



(b)

13.4 Tile drains (a) and sampling jugs (b) at the University of Guelph Campus d' Alfred experimental plots.

drainage water beneath experimental plots having received raw manure and digestate treatments.

The University of Guelph study consistently demonstrated higher flow-weighted mean NO_3^- -N concentrations in plots having received treatments compared with control plots (no treatment), indicating soil amendments will increase NO_3^- -N concentrations from background levels in drainage

Table 13.8 Flow-weighted mean NO_3^- -N concentrations in tile drains at University of Guelph Campus d' Alfred experimental plots

Plot treatments	Mean NO_3^- -N concentration in tile drains (mg/l)
Spring 2009	
Raw manure	6.4 ± 1.4
Digestate	8.8 ± 1.7
Control (no treatment)	2.2 ± 0.9
Spring 2010	
Raw manure	5.8 ± 2.3
Digestate	6.1 ± 1.9
Control (no treatment)	2.0 ± 0.3

Source: Data collected by University of Guelph.

waters. Differences in mean NO_3^- -N concentrations in drainage waters between raw manure and digestate treated plots were not significant ($p > 0.05$). The mean drainage NO_3^- -N concentrations from the clay plots were consistently below 10 mg/l – much lower than the reported mean drainage concentrations ranging from 13 to 28 mg/l in sandy and silt loam plots (Jemison and Fox, 1994; Stoddard *et al.*, 2005; Powell *et al.*, 2011).

The impact of land application of digestate on NO_3^- -N leaching to tile drains may be similar to that of raw manure or inorganic fertilizer. Strategies should be implemented to reduce NO_3^- -N drainage losses, including applying appropriate rates for N application, improving timing of application, planting cover crops and reducing tillage (Dinnes *et al.*, 2002).

13.3.6 Bacteria migration to drainage tiles

The land application of agricultural residues can have a direct impact on bacterial concentrations in groundwater, surface water and soil, where leachate from manure-amended fields reaching subsurface tile drains has been shown to have concentrations exceeding background levels (Abu-Ashour *et al.*, 1994; Jamieson *et al.*, 2002; Unc and Goss, 2004; Goss and Richards, 2008). The survival of enteric bacteria can be influenced by several factors, including soil moisture, soil type, pH, temperature and nutrient availability (Abu-Ashour *et al.*, 1994; Goss *et al.*, 2001; Jamieson *et al.*, 2002).

The survival of enteric bacteria in manure-amended soils increases with high moisture content, where moisture retention is linked to soil particle size distribution and organic matter content (Jamieson *et al.*, 2002). Abu-Ashour *et al.* (1994) explain that there is an increased survival of bacteria with increased organic matter content in soils. Furthermore, finer soils (e.g. clay and humic substances) increase water retention, which ultimately increases

Table 13.9 Flow-weighted geometric log mean pathogen indicator concentrations in tile drains at University of Guelph Campus d'Alfred experimental plots

Plot treatments	<i>E. coli</i> (log CFU/100 ml)	<i>Salmonella</i> (log CFU/100 ml)
15 days after land application (total precipitation = 11 mm)		
Raw manure	1.1 ± 0.1	2.2 ± 1.1
Digestate	1.2 ± 0.1	1.6 ± 0.3
Control (no treatment)	1.2 ± 0.1	1.7 ± 0.6
60 days after land application (total precipitation = 161 mm)		
Raw manure	3.4 ± 2.0	3.6 ± 2.1
Digestate	3.0 ± 1.5	3.1 ± 1.5
Control (no treatment)	1.4 ± 0.1	1.7 ± 0.1

Source: Data collected by University of Guelph.

bacterial survival. Chandler and Craven (1980) found *E. coli* cells were able to survive dry loam soil conditions but proliferated once moisture was restored. Bacterial survival is also favoured by cooler temperatures and neutral pH, with pH of 6 to 7 being optimum (Abu-Ashour *et al.*, 1994; Jamieson *et al.*, 2002). Goss *et al.* (2001) reported that *E. coli* O157:H7 can survive for up to 100 days under cold soil temperatures (<5°C). It should be noted that freezing and thawing of soils reduces bacterial survival.

Nutrient availability is a key factor in bacterial survival in soils, where organic matter increases the retention of nutrients and provides a C source. Low N availability can lead to increased bacterial mortality (Abu-Ashour *et al.*, 1994; Jamieson *et al.*, 2002). Goss *et al.* (2001) explain that the concentration of microorganisms in manure at the time of land application is important to the transport of the organisms and eventual contamination of water resources. It can be anticipated that the lower bacterial concentrations in digestate will lead to reduced bacteria migration to drainage tiles (also see Chapter 12 of this handbook).

In the same University of Guelph field study described in the previous section, *E. coli* and *Salmonella* pathogen indicators were used to monitor bacterial migration to drainage tiles comparing plots treated with dairy manure and digestate. Table 13.9 summarizes the flow-weighted geometric log mean *E. coli* and *Salmonella* concentrations in the tile drains.

After the first 15 days following land application of raw manure and digestate, the mean *E. coli* and *Salmonella* counts in the subsurface drains were similar to those found in the controls plots (no treatment). During this 15-day period there was only 11 mm of precipitation. At 60 days after land application, with 161 mm of precipitation, mean bacteria counts were 2-log

higher than the control plots. The data presented no significant effect between soil amendments on bacteria numbers in the drainage tile water. Although the digestate applied to the plots was 2-log lower in bacterial concentrations than the raw manure, these lower bacterial counts in digestate did not translate to lower bacterial counts in drainage water from plots treated with the two manure types. This may be due to the heavy clay soil type in the plots, which slowed down the migration of bacteria through the 1 m of soil before reaching the drainage tiles, thereby masking the fact that fewer bacteria were actually applied to the plots receiving digestate. Bacterial migration in sandy soils may prove to be quite different.

It has been established that the land application of manure and digestate can impact bacteria concentrations in drainage water. However, further studies are needed to determine how lower bacteria concentrations in digestate will impact bacterial transport through soils and, ultimately, the contamination of drainage waters.

13.4 Conclusion and future trends

The land application of digestate when compared with raw manure or inorganic fertilizer has shown some differences with respect to environmental and agronomic impacts.

- Increased NH_3 volatilization in soils amended with digestate or raw manure has been observed. Some studies have reported no observed difference between soils treated with raw manure and digestate-amended soils. Ammonia volatilization is highly dependent on climatic conditions, pH and soil infiltration, thereby making data variable. Further field studies are needed to better demonstrate the long-term effect of land application of digestate on NH_3 volatilization under various climatic and soil conditions. Immediate incorporation or injection should greatly reduce NH_3 volatilization.
- Nitrous oxide emissions from digestate-treated plots have been reported to be similar, and sometimes lower, than raw manured plots. It was suggested the C:N ratio and digestible C may have been too low to stimulate denitrification. However, N_2O emission studies using digestate are limited and further studies are needed to better understand gas emission rates under various climatic and soil conditions.
- Odour emissions were significantly lower with the application of digestate rather than manure or inorganic fertilizer, which demonstrates that anaerobic digestion is an important tool in reducing odours.
- The effects on crop yields were variable, from no effect to significant increases in crop yield. Further field studies are needed to better

understand the long-term yield response under various cropping, climatic and soil conditions.

- Nitrate leaching to tile drains has demonstrated similar trends to those observed when raw manure or inorganic fertilizer was land applied. However, further studies need to be conducted to determine the long-term effects of NO_3^- -N leaching with digestate-amended soils under various climatic and soil conditions.
- The land application of manure and digestate can impact bacteria concentrations in tile drainage water. However, further studies are needed to determine whether the lower bacteria concentrations in digestate will impact bacterial transport through soils.

As further information is collected to determine the environmental and agronomic impacts from the long-term land application of digestate, recommendations for best management practices for handling digestate should be developed (see also Chapter 12 of this book). These recommendations can be used to improve nutrient management planning and government regulations.

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Abstract: Biogas contains not only methane, carbon dioxide and water, but may also contain other compounds in small amounts. These impurities can affect the equipment for biogas utilisation, by causing corrosion and mechanical wear, but may also lead to unwanted emissions. Depending on how the biogas is going to be utilised it often needs some form of cleaning to reduce the amount of unwanted impurities. The effects that different impurities may cause when biogas is utilised and technologies to reduce their concentrations are reviewed in this chapter.

Key words: biogas composition, impurities in biogas, biogas cleaning.

14.1 Introduction

Biogas contains not only methane, carbon dioxide and water, but may also contain other compounds in small amounts. Although the concentrations of impurities are relatively low they can have a negative effect on utilisation of biogas. The impurities can affect the equipment for biogas utilisation by causing problems such as corrosion and mechanical wear. Impurities can also lead to unwanted emissions when the biogas is combusted during utilisation.

14.2 Biogas characterisation and quality standards

14.2.1 Biogas composition

The most common impurities in raw biogas are hydrogen sulphide, ammonia, oxygen and nitrogen; which ones are found depends primarily

Table 14.1 Typical composition of landfill gas and biogas from an anaerobic digester (injection of gases from non-conventional sources into gas networks)

Compound	Unit	Landfill gas	AD gas
Methane	mol-%	30–60	50–80
Carbon dioxide	mol-%	15–40	15–50
Nitrogen	mol-%	0–50	0–5
Oxygen	mol-%	0–10	0–1
Hydrogen sulphide	mg/m ³	0–1000	100–10000
Ammonia	mg/m ³	0–5	0–100
Total chlorine	mg/m ³	0–800	0–100
Total fluorine	mg/m ³	0–800	0–100
Siloxanes	mg/m ³	0–50	

on which substrates and method were used for the biogas production. Typical compositions of biogas and landfill gas are shown in Table 14.1.

Impurities occur in raw biogas for different reasons. Some impurities are present in the substrate that is fed into the reactor; they will evaporate in the digester and thus be present in the produced biogas. Examples of such compounds are siloxanes. The amount that evaporates depends on how volatile the compound is and on the temperature in the digester. Water is found in raw biogas, the amount depending on the conditions in the digester. Impurities can also be formed during anaerobic digestion. In anaerobic digestion processes, degradable compounds are degraded into smaller compounds by different microorganisms present in the digester. In the final step of biogas formation in a digester, methane is formed either by microorganisms digesting acetic acid or by microorganisms combining hydrogen and carbon dioxide. Depending on how much these compounds evaporate, they can be found in small amounts in the produced biogas. Examples of such impurities are ammonia and hydrogen. Impurities can also be added during the process. For example, oxygen (or air) can be added in small amounts to remove hydrogen sulphide by oxidation and thus small amounts of oxygen (and nitrogen) can be present in the biogas. The nitrogen present in landfill gas occurs as a result of extracting the gas by lowering the gas pressure, causing air to enter the landfill. While the oxygen in the air will mostly be consumed by microorganisms in the landfill, nitrogen will remain unchanged in the extracted landfill gas. The amount of nitrogen present in landfill gas is thus dependent on how the gas is extracted from the landfill and if a low pressure is used. In the following sections, the most common impurities in raw biogas are reviewed in terms of their origin and how they may affect biogas utilisation.

Carbon dioxide

Apart from methane, carbon dioxide is the main component in biogas. It is formed during the decomposition of the different types of substrates used for biogas production. The transformation of substrates into biogas is a complex process that involves several steps and different types of microorganisms. Carbon dioxide is formed in the different steps and acts as an electron acceptor for the methane-producing bacteria. The carbon dioxide will decrease the volumetric energy content in the biogas. If high volumetric energy content is important (e.g. when the gas is used as a vehicle fuel or injected into the gas grid), the carbon dioxide can be considered an impurity that should be removed. For other applications, such as power and heat generation, it does not usually cause problems. However, water that condensates and carbon dioxide will form carbonic acid.

Water

Since water is always present during anaerobic digestion some of it will evaporate in the digester and thus be present in the produced biogas. Biogas leaving the digester is therefore always saturated with water. The amount of water in the biogas depends on how much water can be present before the gas becomes saturated with water. The water concentration corresponding to saturation in biogas depends on the pressure and the temperature inside the digester. Water in raw biogas can cause problems downstream from the digester. It can, for example, cause corrosion in pipelines in the presence of other compounds such as carbon dioxide, due to formation of carbonic acid. Another negative effect is that water lowers the energy content of the gas and can thus affect energy utilisation from the gas. Even in the case when the raw biogas is dried before utilisation, water is formed when biogas is combusted. Depending on the temperature and pressure downstream from the combustion stage, water may condense and cause problems in downstream heat exchangers and exhaust components.

Hydrogen sulphide

Another common impurity in biogas and landfill gas is hydrogen sulphide. Other sulphur-containing impurities may also be present in raw biogas, but hydrogen sulphide is the most common. Hydrogen sulphide is formed by bacteria that have the ability to reduce sulphate present in the digester to hydrogen sulphide. These bacteria are present in the digester and compete with methane-forming bacteria for the same substrate but, instead of forming biogas, hydrogen sulphide is formed. Sulphate-rich substrates include stillage, macroalgae and some substrates from the paper industry.

Hydrogen sulphide is also formed during digestion when proteins containing sulphur, such as cysteine and methionine, are digested. In landfill gas, hydrogen sulphide may also originate from gypsum. The presence of hydrogen sulphide during utilisation of biogas can lead to corrosion since it forms sulphuric acid in combination with water. The combustion of biogas containing hydrogen sulphide will lead to emissions of sulphuric acid formed during combustion. It is also important to note that hydrogen sulphide is highly toxic and can result in serious health risks.

Oxygen and nitrogen

Since biogas is formed under anaerobic conditions, neither oxygen or nitrogen are usually present in biogas but they can be found if air is allowed (or manages) to enter somewhere in the system. If oxygen is present it will be consumed; nitrogen in the raw biogas can thus be a sign of air leakage into the digester. Sometimes air is consciously added to the process to reduce hydrogen sulphide as a way of cleaning the biogas. It is more common for nitrogen to be found in landfill gas, and there may also be small amounts of oxygen, due to the fact that the extraction of landfill gas can cause a low pressure in the landfill, which will result in air being sucked in. Oxygen can lead to flammable mixtures being formed with the methane in the biogas and oxygen content thus has to be carefully controlled.

Ammonia

Ammonia is an impurity often found in raw biogas; it is formed in the digester during hydrolysis of materials containing proteins, such as slaughterhouse wastes. High levels of ammonia in the digester can cause inhibition of methane production in the digester.

Volatile organic compounds

Volatile organic compounds are different types of organic compounds found in various concentrations in biogas. The type of compounds and their concentrations depend on the substrate used for biogas production; examples are alkanes, siloxanes and halogenated hydrocarbons.

Siloxanes are compounds used in products such as fire retardants, shampoos and deodorants. Siloxanes are molecules that are composed of units of R_2SiO , in which R is a hydrogen or a hydrocarbon group, Si is silicon and O oxygen. If siloxanes are present in the substrate entering the digester, these compounds will also be found in small amounts in the produced biogas due to the fact that some of these compounds evaporate. Siloxanes can thus be found in biogas produced from sewage sludge. The

temperature in the digester will determine how much evaporation into the biogas will occur. Low molecular weight siloxanes will evaporate to a higher extent than others. Siloxanes can also be found in landfill gas due to the evaporation of siloxanes in the landfill. During combustion, siloxanes form siloxane oxide, which can cause damage to engines. The formed siloxane oxide is insoluble and will form unwanted depositions on combustion equipment.

Halogenated hydrocarbons are hydrocarbon molecules containing chlorine, bromine or fluorine. They can be present in raw biogas due to the volatilisation of halogen-containing material in landfills, for example. Hydrogenated hydrocarbons can cause corrosion and acidification when combusted, due to the formation of acids (e.g. hydrochloric acid).

Particles

Particles are often present in raw biogas. In many cases, particulates form the nuclei onto which drops of water condense. Particles can cause wear of equipment due to their abrasive properties.

14.2.2 Biogas utilisation and quality demands

How clean the biogas needs to be depends on how the biogas is going to be utilised. The energy in biogas can be utilised as heat or heat and power or can be converted to kinetic energy when used as vehicle fuel. Before utilisation, cleaned and upgraded biogas can also be injected into the gas grid. There are different aspects on quality demands for biogas utilisation. The technical aspect is of course very important and relates to limitations on the equipment used, but it is also important to know which gas the equipment in question is certified for and how the equipment can be adjusted for other gas qualities. In general, it can be said that the cleaner the gas is, the lower the maintenance cost will be. Gas cleaning can thus sometimes be a compromise between cleaning and maintenance costs. When evaluating biogas composition and its impurities one cannot look at each impurity individually since the different impurities also affect each other; for example, carbon dioxide and hydrogen sulphide form acids when dissolved in water and these acids then cause corrosion.

Quality demands on biogas for heat and power production

Boilers are used for heat production from biogas. Compounds that can cause problems in a boiler are hydrogen sulphide, particles and siloxanes. For condensing boilers, in which the flue gas is cooled down and the water in the gas condensates, hydrogen sulphide will form sulphuric acid with

water, which may then cause corrosion. Particles and siloxanes can also cause problems since they can clog small parts (e.g. tubes) in the boiler. However, small boilers are often not designed for the utilisation of raw biogas, but only for natural gas; this opens up the possibility of using upgraded biogas.

Industrial boilers are sometimes certified for using raw biogas. As with small boilers, hydrogen sulphide together with condensed water may cause corrosion. Since the components in large boilers are not so small, there are less problems with particles and siloxanes than in small boilers. After the boiler is adjusted to a certain biogas composition it should not vary too much. However, if the boiler is equipped with an oxygen or carbon monoxide sensor in the flue gas, more variations in gas composition can be tolerated.

Microturbines are generally flexible in operation and tolerant to trace compounds. Biogas that is burned in a microturbine is first compressed, which means that it has to be dry in order to avoid condensation of water from the gas. Some microturbines can tolerate hydrogen sulphide concentrations of up to 1000 ppm, but particles and siloxanes can cause problems in microturbines.

As with microturbines, the gas used in gas turbines is compressed, which sets quality demands on the gas when it comes to water content. Quality demands on the biogas used in gas turbines must often be discussed and agreed with the equipment producer. Gas turbines can tolerate different biogas compositions, but must be more finely adjusted to perform well. Producers of gas turbines often specify a maximum tolerance of hydrogen sulphide and particles in the biogas fuel.

Engines used for heat and power production can tolerate different gas compositions but, as with other applications, hydrogen sulphide can cause problems. Siloxanes can also cause problems.

Fuel cells can also be used for power production from biogas. Different types of fuel cells use different fuels and have different sensitivities to impurities in the gas. High-temperature fuel cells are more fuel flexible and are also more tolerant to impurities in the fuel. High-temperature fuel cells (e.g. molten carbonate fuel cells (MCFCs)) can use methane from biogas as a fuel, but for fuel cells that operate at lower temperature (e.g. proton exchange membrane (PEM) fuel cells), the biogas has to be catalytically reformed to hydrogen which can then be used as a fuel. Compounds that can be toxic to fuel cells and thus should be removed from the biogas are hydrogen sulphide, halogenated hydrocarbons, ammonia and siloxanes. These compounds should also be avoided in the catalytic reforming process prior to reformed biogas being used in PEM fuel cells operating at low temperature.

Quality demands on biogas for transport fuel or grid

For biogas to be used as transport fuel, it is advantageous to use biogas with a high energy content; cleaned and upgraded biogas is thus preferred. However, lower concentrations of methane could work from a technical point of view. Water in the gas can cause problems; for example, it may freeze and clog the system when the pressure drops. Carbon dioxide can have a corrosive effect, but only in combination with water; the same is true for hydrogen sulphide. Different standards are used for biogas used as vehicle fuel. Sweden has a standard specifically for biogas to be used as vehicle fuel (SIS, 1999), which regulates the content of methane, hydrogen sulphide and water. Other standards have been published in the USA (SAE International, 1994), Switzerland (ISO, 2006) and Germany (DIN, 2008); the UNECE Vehicle Regulations also apply (UNECE, 1958). Standards are currently being developed by the European standards work group CEN/TC 408 – Biomethane for use in transport and injection in the natural gas grid.

If the biogas is going to be injected to the gas grid it has to fulfil the gas quality demands for the grid, independent of the final use of the gas. This means that if the biogas is going to be used in a boiler, but transported to the boiler via the gas grid, it has to fulfil the quality demands for the gas grid, which are in general higher than those for the boiler itself. More details on biogas upgrading are given in Chapter 15 of this book.

14.3 Biogas cleaning techniques

This section reviews different cleaning techniques for the most common impurities found in raw biogas. The removal of carbon dioxide is covered in Chapter 15.

14.3.1 Water

Water can be removed by changing the parameters that affect the solubility of water in the gas, i.e. pressure and temperature. Water vapour will condense if the pressure is increased or if the temperature is lowered, since the concentration corresponding to saturation in the gas will then decrease. Thus, technologies to remove water from biogas are compression and/or cooling. Water can also be removed by absorption and adsorption. Other impurities that can dissolve in water, like particles and siloxanes, will be removed together with the water and this has to be considered when designing systems for disposal of the water.

Cooling and/or compression

Cooling can be achieved by burying the biogas pipeline in the ground and equipping the pipeline with water drains or condensate traps. Other technical installations for water compression cooling are demisters and cyclones.

Adsorption

Adsorption can be achieved using silica, aluminium oxide, magnesium oxide, activated carbon or zeolites. Regeneration is usually achieved by increasing the temperature and/or decreasing the pressure. Usually, two columns work in parallel – one is adsorbing while the other one is being regenerated.

Absorption

Absorption can be done in glycol solutions (e.g. ethylene glycol, diethylene glycol, triethylene glycol) that bind the water by absorption (regenerated by heating) or by the use of hygroscopic salts. The salt is dissolved when it absorbs water and the salt is usually not regenerated.

14.3.2 Hydrogen sulphide

Hydrogen sulphide can be removed in the digester itself or after the digester. For some upgrading techniques it is very important to remove hydrogen sulphide before upgrading since it will otherwise have a negative effect on the upgrading plant; for example, in pressure swing adsorption (PSA) it will be irreversibly bound to the adsorption material. For other upgrading technologies it is less of a problem and for some it is removed (at least to some extent) in the upgrading process itself. Hydrogen sulphide has a higher solubility than carbon dioxide in water and will thus be removed together with the carbon dioxide in the water scrubber. For more information about biogas upgrading see Chapter 15. The technologies used for the removal of hydrogen sulphide can be divided into biological, physical or chemical methods.

Biological removal

If air/oxygen is injected into the digester, hydrogen sulphide will react with oxygen and form elementary sulphur through biological oxidation. Some sulphate dioxide may also be formed. The oxidation is catalysed by *Thiobacillus* bacteria that are normally present in the digester. Usually, some

mechanical structure is installed in the top of the digester for these bacteria to grow on. A drawback with this technology is that if too much oxygen is injected it will affect the digestion process negatively. Care also has to be taken to ensure that explosive mixtures between methane and oxygen are not formed. Depending on how the biogas is going to be utilised, traces of oxygen and nitrogen (which will remain after the oxygen has been consumed if air is injected) may be a problem if the gas is going to be upgraded since it is hard to separate nitrogen from methane. The same principle that is used for removal in the digester can also be used after the digester, using a biological filter with bacteria that can oxidise hydrogen sulphide. In this case, a column filled with large surface area carriers onto which bacteria can grow are used and the biogas is cleaned by letting it pass through the column. The sulphur that is formed remains in the liquid phase in the filter.

Physical removal

Hydrogen sulphide can be removed from raw biogas using absorption technologies with water or organic solvents. One of the oldest methods for hydrogen sulphide removal is sodium hydroxide scrubbing. Chemical absorption can also be used and, in that case, the liquid medium is a water solution containing NaOH, FeCl₂ or Fe(OH)₃. Hydrogen sulphide reacts and forms sulphide or sodium hydrogen sulphide. A caustic solution has increased solubility compared with water. The liquid can be regenerated with microorganisms that are able to biologically oxidise sodium sulphates. Organic solvents that have greater solubility of hydrogen sulphide than water can also be used. The liquid is regenerated by air stripping, which can give elementary sulphur. Another alternative is to use a process in which the biogas is cooled down so that liquid carbon dioxide is formed in which hydrogen sulphide (but also other impurities) is dissolved.

Hydrogen sulphide can also be removed by adsorption using activated carbon. To make the removal more efficient, the carbon can be dosed with KI or H₂SO₄, which will catalyse between added air and the hydrogen sulphide. If the raw biogas is going to be upgraded, hydrogen sulphide will be removed together with carbon dioxide to some extent, but the level of removal depends on the upgrading technology used. However, it is often advantageous to remove it before the upgrading process. In a PSA upgrading plant, hydrogen sulphide will be removed, but since it is irreversibly bound to the activated carbon it is advantageous to remove it before upgrading.

Chemical removal

To prevent the presence of hydrogen sulphide in the produced biogas, iron ions (Fe^{2+} or Fe^{3+}) in the form of FeCl_2 , FeCl_3 or FeSO_4 can be added to the digester. This produces insoluble iron sulphide (FeS), which will precipitate in the digester. The iron sulphide will leave the digester together with the digestate. The reactions involved are:



This is done in sewage sludge treatment plants for simultaneous removal of phosphate. Hydrogen sulphide can also be removed by this principle after the digester, in a reaction with iron oxide coated materials (e.g. wood chips) to form iron sulphide. The process operates with two columns. Iron oxide is regenerated by heating and/or exposure to oxygen. Eventually, the material becomes saturated with sulphur and cannot be regenerated.

14.3.3 Other impurities

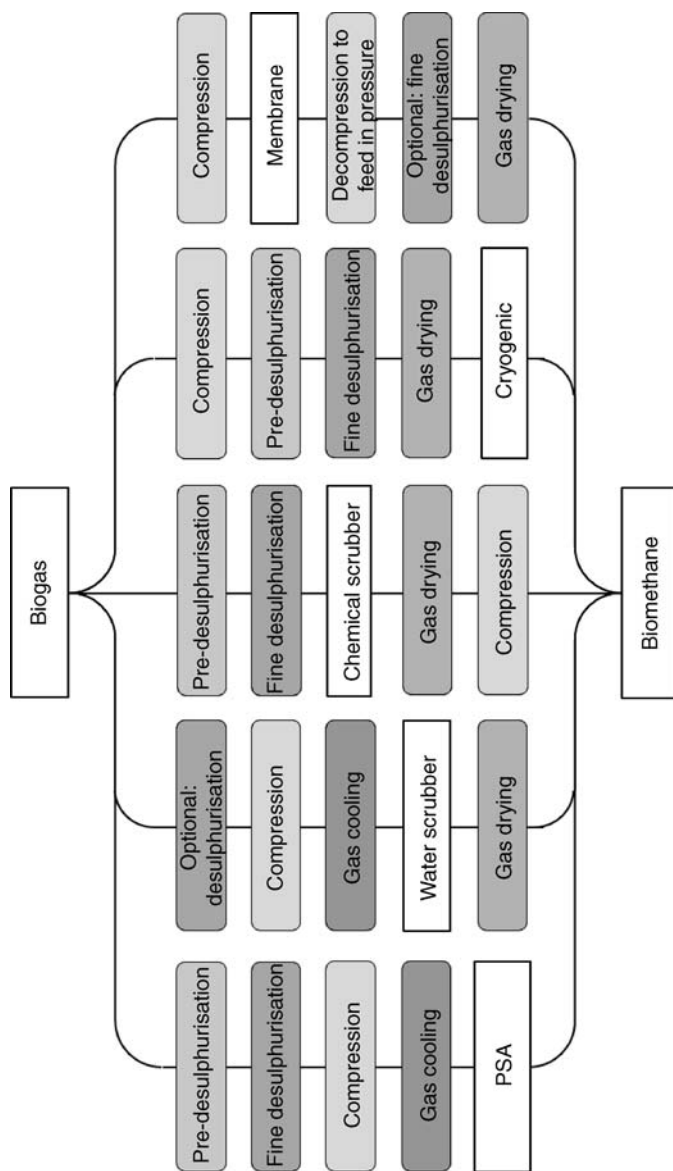
Oxygen and nitrogen can be removed by adsorption using activated carbon, molecular sieves or membranes; they are also removed, to some extent, in some desulphurisation processes and some upgrading processes. However, these gases are difficult to remove and their presence should be avoided if utilisation of the gas limits the levels of oxygen and nitrogen (e.g. if the gas is injected to the gas grid or used as vehicle fuel).

Ammonia in raw biogas is usually removed when the gas is dried, since ammonia will dissolve in water. Ammonia is also removed simultaneously when the gas is upgraded and a separate cleaning step is often not necessary.

Siloxanes can be removed by absorption with organic solvents, strong acids or strong bases, by adsorption with silica gel or activated carbon, or in a cryogenic process (Ryckebosch *et al.*, 2011). Some particles are removed when the gas is dried or can be removed by filters or cyclones. Halogenated hydrocarbons can be removed by adsorption with activated carbon. They are also removed in many of the upgrading technologies.

14.4 Biogas cleaning in combination with upgrading

When biogas is upgraded, carbon dioxide is removed from the methane in order to increase the volumetric energy content in the gas. If the biogas is going to be upgraded this affects the set-up of the cleaning step (Fig. 14.1). Some impurities are removed in the upgrading step, but this is dependent on



14.1 Schematic illustration of different combinations of biogas cleaning processes and biogas upgrading processes (adapted from Schmuderer, 2010).

which upgrading technology is used. However, some impurities are also harmful to the upgrading process and the impurities have to be removed before upgrading takes place. For example, for some upgrading processes (PSA, chemical scrubbers and cryogenic upgrading), it is recommended that hydrogen sulphide be removed before upgrading.

14.5 Conclusion and future trends

Increasing biogas production by digesting more of the available substrates is a promising way of increasing the share of renewable energy in society. The increase could come from the digestion of various types of substrates, including homogeneous materials such as manure and energy crops and mixed materials such as segregated household waste. The substrates used will affect the composition of biogas which, together with the utilisation method, will determine the need for cleaning of the biogas. Manure is an often unused potential substrate for biogas production in many countries. However, manure has a low dry matter content and contains a lot of water, so it is not economical or environmentally sound to transport it over long distances. For this reason, manure digestion would have to take place in small-scale digesters. This could lead to a potential for development of simple cleaning methods adjusted for small-scale applications. Large volumes of landfill gas are still produced in many countries. Utilisation of more landfill gas could, on the other hand, lead to the development of more advanced and large-scale cleaning methods.

Biogas can be utilised in different ways and it is becoming more and more important to also utilise the heat when power is produced. Increasing amounts of biogas are also being used as transport fuel or for injection to the grid and these utilisation paths demand a higher quality of gas.

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Abstract: Compared with other utilization paths of biogas, upgrading of biogas to biomethane offers several advantages and has thus become of increased relevance in the last decade. This chapter describes past developments as well as the current state of upgrading, especially in Europe. Specifics of biogas cleaning combined with biogas upgrading will be described. The chapter focuses on technical aspects of upgrading and off-gas treatment methods as well as on economic aspects of biomethane provision.

Key words: biomethane, biogas upgrading, purification, natural gas, physical absorption, physisorption, chemical absorption, chemisorption, adsorption, molecular sieve, pressure swing adsorption (PSA), water scrubber, amine scrubber, membrane separation, regenerative thermal oxidation (RTO), catalytic oxidation, flameless oxidation.

15.1 Introduction

Upgrading of biogas to biomethane has increased in the last decade, especially in Europe. Upgrading of biogas to biomethane offers several advantages over direct utilization of raw biogas (e.g. in combined heat and power plants (CHPs) at the site of production). In remote areas, heat consumption over the whole year is often not guaranteed and thus heat has to be vented. Biogas upgrading and grid injection of biomethane enables transportation of the gas to places where the complete energy (power and heat) is needed, thus offering the chance to increase the overall efficiency of gas utilization. In summary, biomethane offers the following advantages:

- temporary decoupling of production and utilization
- local decoupling of production and utilization

- storage capability
- flexibility regarding several utilization paths: electricity (combined with full utilization of heat); heat (combined with power or in natural gas burners); vehicle fuel (for natural gas vehicles); and primary product for the chemicals industry.

Biomethane is thus set to become an important building block of a renewable-based future energy system.

15.2 Development and overview of biogas upgrading

Biogas upgrading to biomethane has a worldwide history of nearly a century. For example, in Germany [1], Switzerland and elsewhere [2], wastewater treatment plants operated sewage gas upgrading plants from the mid-1930s to the mid-1960s. This biomethane was used mainly for the provision of vehicle fuel for passenger cars driven by Otto engines [1] and waste collection trucks [2]. This kind of biomethane provision was discontinued in the mid-1960s because of discontinuations of preferential tax treatment, technical developments and cheap oil imports [1].

Nowadays, biogas upgrading is especially focused on Europe and partly North America. Outside of these two continents, there are only a few plants in operation. From the start of the 1980s, several projects where biogas has been upgraded to natural gas quality, have been described.

In Moenchengladbach, Germany, a plant upgrading sewage gas operated from 1982 to 1996. During this period, around 20 million m³ of biomethane (L-gas quality) were injected into the local natural gas grid. As upgrading technology, a water scrubber with a raw gas capacity of 400 m³/h was used [1, 3, 4].

Before 1985, a project in Christchurch, New Zealand, started operation. In this project, biomethane for utilization as vehicle fuel was produced by a water scrubber with a capacity of 60 m³/h [5, 6].

In Stuttgart, Germany, sewage gas was upgraded from 1986 to 1993. Roughly 5 million m³ biomethane (H-gas quality) were injected into the local natural gas grid. The upgrading plant (chemical scrubber using monoethanolamine (MEA)) had a capacity of 400 m³/h of raw sewage gas [3].

In the USA, the first biogas upgrading projects also began in the 1980s. Four separate projects in Staten Island (1981), Renton (1984), Cincinnati (1986) and Houston (1986) with an overall raw gas upgrading capacity of > 30,000 m³/h produced biomethane from landfill and sewage gas for grid injection. As upgrading technologies, two Selexol[®] scrubbers, one water scrubber and one pressure swing adsorption (PSA) were used [7].

In The Netherlands, several landfill gas upgrading projects were implemented from 1987 to 1991. All the projects injected biomethane into

natural gas grids; what can be seen as an exceptional case for the utilization of landfill gas in Europe. In the following years, especially in Sweden and Switzerland, many new upgrading projects were initiated. For more than 10 years, Sweden and Switzerland were the leading countries in biogas upgrading to biomethane.

Currently, the most ambitious activities can be found in Germany. The German government defined targets for the production and sustainable utilization of biomethane and, as a consequence, 83 biogas upgrading plants were in operation by the end of 2011. Figure 15.1 shows the number of biogas upgrading plants and raw biogas upgrading capacities in Europe at the end of 2011.

Figure 15.2 gives an overview of the development of the upgrading capacity of identified European biogas upgrading plants since 1987. At the end of 2011, there were 200 plants in operation. These plants have an upgrading capacity of $\sim 162,000 \text{ m}_n^3/\text{h}$ raw biogas to biomethane. This upgrading capacity corresponds to an energetic capacity of 1.1 GW (upper heating value, H_s) related to biomethane (assuming average 60% methane content in the raw biogas and 1% methane loss in the upgrading process).

15.3 Biogas cleaning and upgrading technologies

To be able to inject biogas into natural gas grids or for direct utilization as vehicle fuel, it is necessary to clean and upgrade the raw biogas. Cleaning means the separation of undesired gas compounds and upgrading refers to the separation of CO_2 .

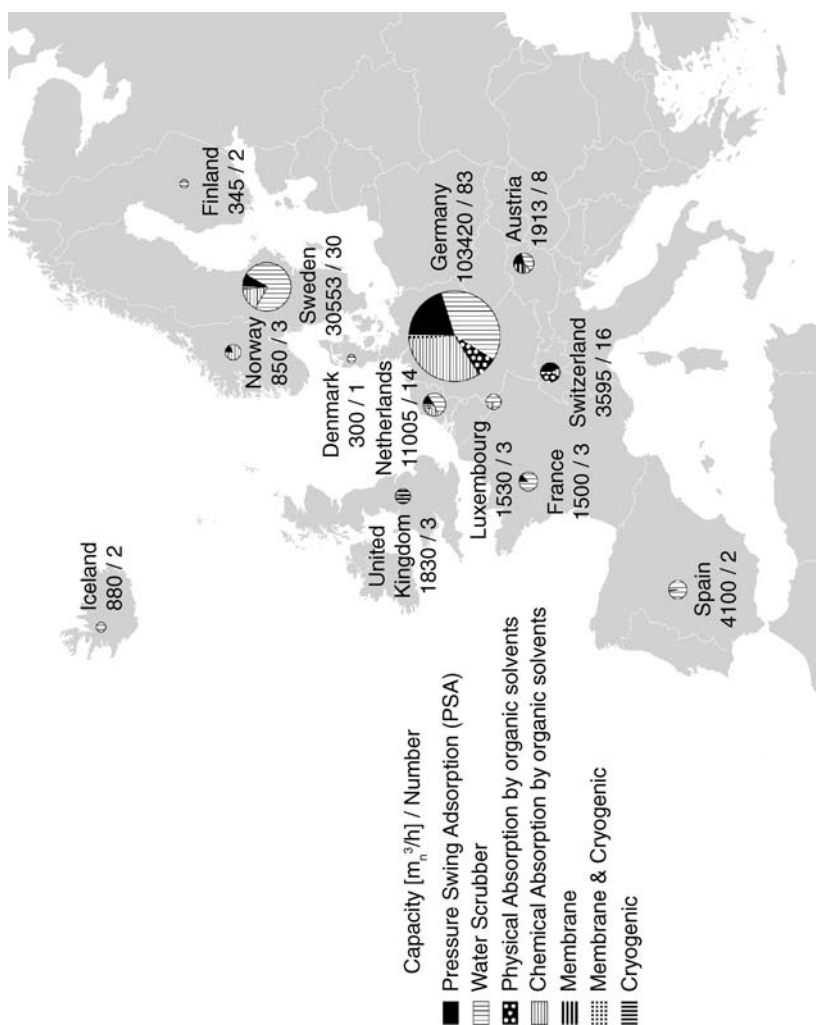
15.3.1 Biogas cleaning combined with biogas upgrading

The necessity and applicable technologies or strategies for biogas cleaning as a preliminary step to upgrading differ compared to the case when the biogas is to be used directly as raw gas (e.g. in combined heat and power (CHP) or directly for heat production). The main parameters that define the necessary biogas cleaning steps are

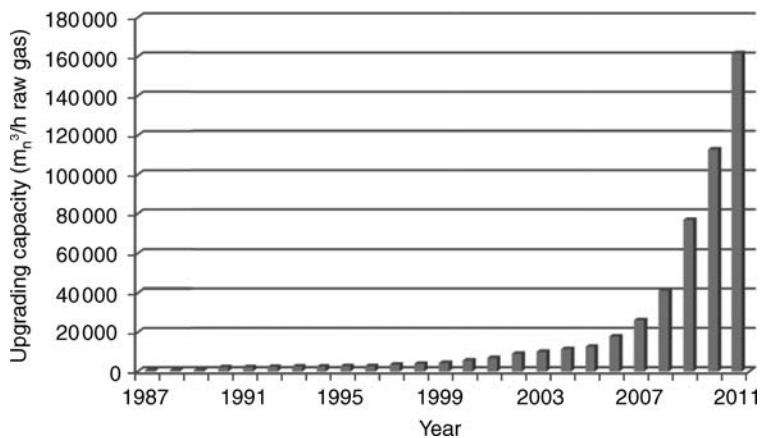
- composition and origin of the raw biogas (e.g. biowaste, sewage sludge, energy crops, manure, etc.)
- subsequent upgrading technology according to the specification of the upgrading plant provider [8].

Humidity removal and drying

Biogas leaving the digester is saturated with water vapour. This water has to be separated from the gas flow to avoid disruptions in operation of the



15.1 Overview of numbers of plants and raw biogas upgrading capacities in Europe as of December 2011 (Copyright: Fraunhofer IWES, 2012).



15.2 Upgrading capacity of European biogas upgrading plants in the period 1987–2011 related to raw biogas (Copyright: Fraunhofer IWES, 2012).

subsequent biogas upgrading steps. Furthermore, it is necessary to maintain the limiting water concentrations for natural gas grid injection as well as for utilization as vehicle fuel. The removal of water is usually carried out at two positions in the upgrading chain.

- If compression is necessary before the biogas upgrading step (e.g. scrubber column, molecular sieve or membrane module), the raw biogas is cooled after the compressor(s). Because the biogas is heated by the compression, humidity condenses while the gas cools down. This is done to avoid unwanted condensation effects in the downstream system.
- If using scrubber technologies there is also a need to dry the upgraded product gas after the outlet of the scrubber column because the gas leaves this column saturated with humidity. For drying the upgraded gas, adsorptive drying systems such as molecular sieves or silica gel are most commonly used.

Usually, no final drying is required when using glycol compounds as the absorbent in the scrubber column. In these systems, simultaneous absorption of humidity takes place [8].

Desulphurization

Depending on the composition of the fresh substrate, raw biogas may contain hydrogen sulphide (H_2S) in concentrations of $<100 \text{ mg/m}_n^3$ up to $10,000 \text{ mg/m}_n^3$ [7] – in exceptional cases up to $30,000 \text{ mg/m}_n^3$ [9]. During oxidation (burning) sulphurous acid can be formed. To avoid corrosion effects in plant components and to ensure the quality requirements for grid

injection or use as vehicle fuel, desulphurization is required. Basically, two steps of desulphurization can be differentiated – primary and precision desulphurization; the first reduces the H_2S level to <500 ppm (mostly down to ~ 100 ppm) while the second is for fine tuning according to the specifications of the upgrading plant and/or the requirements for gas utilization or grid injection. Furthermore, desulphurization methods can be also divided into internal/external methods (inside or outside of the digester) with or without addition of oxygen [8].

For primary desulphurization in agricultural biogas plants without biogas upgrading, the internal method is used as a standard application and involves dosing of air into the gas space of the digester [8]. The H_2S is then biologically oxidized to elementary sulphur. The main advantage of this sulphur reduction step is that it is a very cheap technique because only air and a simple membrane pump combined with a flow meter are needed. At the same time, this economic advantage becomes the main disadvantage because N_2 is inert and does not react in the gas flow. As a consequence of this, N_2 is accumulated in the raw gas. Because most upgrading technologies are not able to separate N_2 it will be found in nearly the same amounts but in higher concentrations in the biomethane. Air addition for desulphurization is thus commonly not the method of choice before gas upgrading. There are two exceptions, as follows.

- If biomethane is injected into natural gas grids with low heating values (L-gas grids), it will be necessary to decrease the CH_4 concentration, and respectively the heating value of the biomethane, by mixing with air. In that case it can be advantageous to apply this cost-efficient desulphurization method.
- If using pure oxygen instead of air for dosing into the raw gas flow, the above-described dilution effect by N_2 does not occur. Pure oxygen can, for example, be provided directly at the plant by a small PSA system.

In both cases (using air or pure oxygen), added oxygen will be found in the gas flow after the biological desulphurization. This becomes an advantage if using an activated carbon filter for the subsequent precision desulphurization. Because this filter needs a small amount of oxygen for the catalytic oxidation of H_2S , this oxygen can be provided automatically by the former dosing.

To avoid the dilution effects with air or oxygen, the primary desulphurization techniques mostly applied when biogas is upgraded to biomethane are

- external biological H_2S reduction with separated absorption/oxygenation steps
- combination of external biological H_2S reduction with a basic scrubber

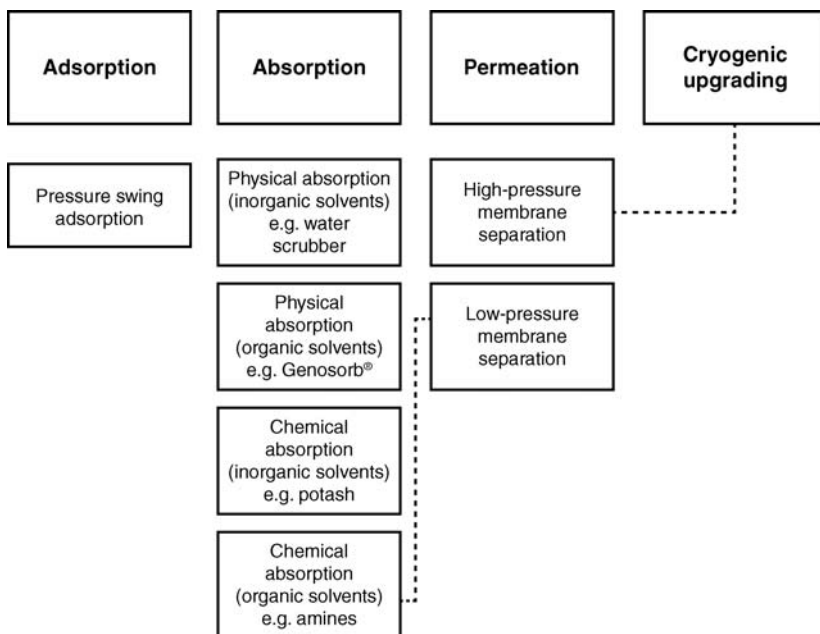
- chemical precipitation using iron salts (sulphide precipitation)
- chemical precipitation using iron hydroxide.

Precision desulphurization can be defined as decreasing the hydrogen sulphide concentration down to concentrations less than 5 mg/m_n^3 [8]. For this purpose, impregnated or doted activated carbon is normally used (catalytic oxidation and following adsorption) and will be found at most biogas upgrading plants [8]. Therefore, it can be considered as state-of-the-art if producing biomethane. Alternatively, chemisorption on iron oxide- or hydroxide-coated materials in an external column can be applied for precision desulphurization. Chemisorption using zinc oxide in external columns is basically also applicable, but currently not state-of-the-art for precision desulphurization of biogas.

15.3.2 Biogas upgrading technologies

The major task for the production of biomethane is removal of CO_2 . Upgrading technologies can be roughly assigned to four main groups (Fig. 15.3)

- adsorption



15.3 Overview of possible biogas upgrading technologies for CO_2 removal; broken lines describe combinations of methods (Copyright: Fraunhofer IWES, 2012).

- absorption
- (gas) permeation
- cryogenic upgrading (to LBG or CBG).

The six most widespread technologies are pressure swing adsorption, water scrubber, physical absorption (using organic solvents), chemical absorption (using organic solvents), high-pressure membrane separation and cryogenic upgrading. Each will be described in turn. Table 15.1 (on next page) compiles the key parameters of these six upgrading technologies and the data in the table will be discussed in the following sections. It is important to note that the upper levels of the specific ranges for electricity and heat demand, as well as for methane losses, are mostly related to old systems. Therefore, these whole ranges do not reflect the state-of-the-art of the current generation of upgrading plants.

Pressure swing adsorption (PSA)

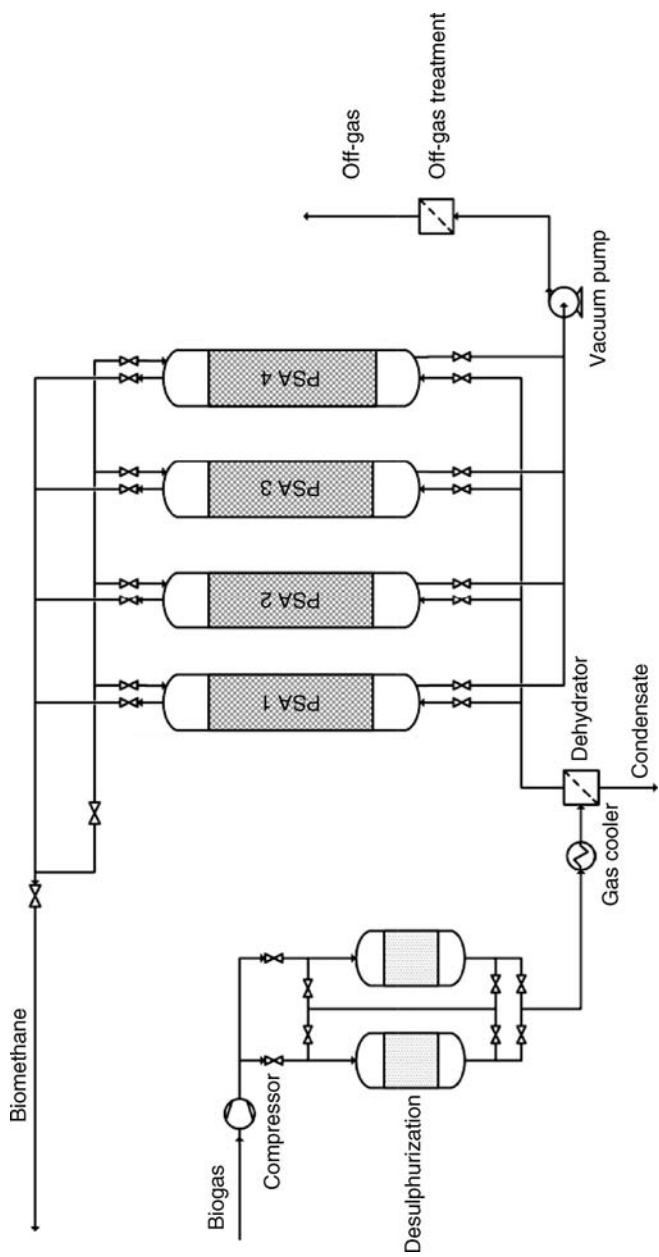
The PSA method (using molecular sieves) is an adsorptive biogas upgrading technology. Adsorption means that gas compounds (adsorbates) are retained on the surface of solids (adsorbents) [27] and are trapped by the size of the molecular sieve. As adsorbents, activated carbon, zeolites or carbon molecular sieves can be used [11]. Low temperatures and high pressures increase the adsorption rate [27]. PSA technology was introduced at a commercial scale in the 1960s [28].

Besides CO_2 , other molecules such as H_2S , NH_3 and H_2O can be co-adsorbed. In practical use, H_2O as well as H_2S are removed before the biogas is injected into the adsorption columns. Water dew points in the product gas of -100 to -80°C can be reached [10]. N_2 and O_2 can also be adsorbed, partly in parallel to CO_2 . From large-scale plant operation it is known that around 50% of the N_2 is separated into the off-gas flow [29]. Typical methane concentrations in the biomethane flow are $>96\%$ [9].

Operation pressures may be in a range of 1 to 10 bar [10]. In most PSA systems the biogas is compressed from 4 to 7 bar [11]. The pressure loss in the system is ~ 1 bar [16]. After precision desulphurization, cooling and removal of water, the cleaned raw gas is injected into an adsorption column where the molecular sieve is located. The operation temperature ranges from 5 to 35°C [10]. The predominant part of the CO_2 is adsorbed on the surface of the molecular sieve while most parts of CH_4 pass it without adsorption. Only a small part of methane is also adsorbed. The product gas leaves the adsorber nearly continuously and the subsequent desorption is done by release of pressure. The first part of the flow is led into an empty column, primarily to build up the pressure there. A further advantage compared with direct outlet of this gas flow as off-gas flow of the overall plant is that a main

Table 15.1 Overview of key parameters of biogas upgrading technologies (Copyright: Fraunhofer IWES, 2012)

	PSA	Water Scrubber	Physical absorption (organic solvents)	Chemical absorption (organic solvents)	Membrane (high pressure, dry)	Cryogenic Sources
Electricity demand (kWh/m ³ BG)	0.16–0.35	0.20–0.30	0.23–0.33	0.06–0.17	0.18–0.35	9–15, 18, 19, 23]
Heat demand (kWh/m ³ BG)	0	0	0.10–0.15	0.4–0.8	0	[14, 17, 19]
Temperature process heat (in the column) (°C)	—	—	40–80	106–160	—	[11, 12, 20]
Operation pressure (bar)	1–10	4–10	4–8	0.05–4	7–20	[7, 10–13, 21, 22, 25]
Methane loss (%)	1.5–10	0.5–2	1–4	~0.1	1–15	[11–13, 16, 17, 19, 21, 24, 26]
Methane recovery rate (%)	90–98.5	98–99.5	96–99	~99.9	85–99	[11–13, 16, 17, 19, 21, 24, 26]
Off-gas treatment recommended (methane loss > 1%)	Yes	Yes	Yes	No	Yes	Yes
Precision desulphurization required	Yes	No	No	Yes (Depending on manufacturer)	Recommended	Yes
Water demand	No	Yes	No	Yes	No	No
Demand on chemical substances	No	No	Yes	Yes	No	No



15.4 Process scheme of the pressure swing adsorption process (Copyright: Fraunhofer IWES, 2012).



15.5 Pressure swing adsorption plant (copyright: Fraunhofer IWES).

part of the in the first column co-adsorbed CH_4 passes the molecular sieve in this second column without adsorption and is therefore available in the product gas flow. After balancing the pressure between these two columns, the pipe between them is closed. The first column is then discharged completely by pressure release down to ambient pressure and is finally evacuated [7, 11]. According to a manufacturer [10] as well as information from a plant operator [30] controllability in the range 40–100% (compared to nominal load) is possible. Figure 15.4 illustrates the PSA process of a four-bed system, but five-bed and six-bed systems are also available; another manufacturer offers rotating valve systems using nine-bed systems. A PSA plant is shown in Fig. 15.5.

The electricity demand varies from 0.16 to $0.35 \text{ kWh}_{\text{el}}/\text{m}_n^3$ raw gas. One technology provider reports specific electricity demands of $0.35 \text{ kWh}_{\text{el}}/\text{m}_n^3$ for their first plants in the mid-1980s but the current (2012) plant generation should be able to reach specific demands of 0.16 – $0.18 \text{ kWh}_{\text{el}}/\text{m}_n^3$ depending on the methane concentration in the raw biogas [10]. Warranty values from the same technology provider are $0.17 \text{ kWh}_{\text{el}}/\text{m}_n^3$ (methane concentration in biogas of 65%) and $0.18 \text{ kWh}_{\text{el}}/\text{m}_n^3$ (methane concentration in biogas of 55%) referring to operation pressures of 3 bar (absolute pressure) [16]. Another plant provider reported specific demands of 0.19 – $0.23 \text{ kWh}_{\text{el}}/\text{m}_n^3$ [31]. One plant operator reported an average specific electricity demand of $0.23 \text{ kWh}_{\text{el}}/\text{m}_n^3$ for an operation pressure of 5.4 bar, methane concentrations in the product gas of 96–97%, energy crops as biogas feedstock and a raw gas capacity of $1000 \text{ m}_n^3/\text{h}$ (start of operation in 2008) [30].

In old systems, methane recovery rates were ~94% (methane slip of ~6%). Current methane recovery rates range between ~97.5 and 98.5% (methane slip of 1.5–2.5%) [10]. Depending on the technology provider, there are also strategies to set up significantly lower methane recovery rates. On the one hand, this is done to be able to use the off-gas flow more efficiently and, on the other, to attain increased methane concentrations in the product gas. Product gas qualities of >99% methane have been reached by accepting methane concentrations of 17–18% in the off-gas flow [32].

Because the off-gas flow contains significant amounts of CH_4 it can be necessary to oxidize it in an off-gas treatment step. The off-gas does not include significant amounts of sulphur, so ‘catalytic oxidation’ and ‘flameless oxidation’ as off-gas treatment technologies are mostly used in large-scale applications [33]. Regenerative thermal oxidation (RTO) would also be possible if sufficiently low methane concentrations were reached in the off-gas flow (e.g. by dilution with air).

Water scrubber

Water scrubbing (see Figs 15.6 and 15.7) is an absorptive method for biogas upgrading using only the inorganic solvent water [13]. Unlike adsorption, absorption implies the dissolution of gas or vapour in a liquid (absorption agent) [27]. Basically, it has to be distinguished between physisorption and chemisorption. Water scrubbing is a typical physisorption based on the reversible absorption by physical bonding forces (Van der Waals force). Low temperatures and high pressures increase the absorption rate [27].

In the water scrubber process, CO_2 and other acidic (e.g. H_2S) and basic (e.g. NH_3) gas components are absorbed in parallel [11]. As a side effect of this method, a precision desulphurization is not necessary because H_2S is also removed from the biogas in the absorption column sufficiently. However, it has to be removed from the off-gas. Typical methane concentrations in the biomethane flow are >96% [9, 13, 34].

After condensate separation, the raw biogas normally passes through two compression stages up to approximately 4–8 bar [13, 15, 35], but partly also up to 10 bar [7]. The applied operation pressures and temperatures in the absorption column depend on the particular provider’s strategy. One system provider adjusts the temperature to a range of 5–10°C [34]. After each compression step, cooling takes place. At this stage, heat uncoupling is also possible. The raw gas enters the absorption column at the bottom. The water flowing through the column from top down is loaded with the absorbed gas (primarily CO_2 and H_2S). Saturated with water, the product gas leaves the column from the top and is sent for adsorption drying [13]. The scrubbing solution (also carrying some CH_4) is, in a first step, decompressed in the so-called flash column to pressure levels of ~2–4 bar



15.7 Water scrubber plant (Copyright: Fraunhofer IWES).

[35]. The gas desorbed at this expansion step leaves the top of the flash column and is returned to the untreated gas flow between the first and second raw gas compression step [35, 36]. This is done to reduce methane slip of the upgrading plant. The water, which at that stage contains mainly dissolved CO_2 and H_2S , enters the desorption column top and is expanded to ambient pressure. Air is blown in at the bottom of the desorption column to assist the degassing of the water [13]. At the end of this process, regenerated water is obtained, which can be re-stored for absorption in the scrubber. The dissolved off-gas leaves the column at the top end of the desorption column. The off-gas still contains some CH_4 and is thus usually treated further [8, 9, 13].

According to manufacturer information [23], controllability in the range 40–100% (compared to nominal load) is possible. One plant operator has reported [30] that controllability in the range 25–110% is possible.

The electricity demand of the process varies from 0.20 to $0.30 \text{ kWh}_{\text{el}}/\text{m}_n^3$ raw gas [11, 13, 23, 34]. Current warranty values of one technology provider are $0.22 \text{ kWh}_{\text{el}}/\text{m}_n^3$ (for larger plant capacities) and $0.25 \text{ kWh}_{\text{el}}/\text{m}_n^3$ (for small plant capacities) referring to product gas pressures of 5 bar (absolute pressure) [15]. A plant operator reported an average specific electricity demand of $0.26 \text{ kWh}_{\text{el}}/\text{m}_n^3$ [30].

Specific water demands are stated by one manufacturer to be $1\text{--}3 \text{ m}^3/\text{day}$ depending on plant size [15]. These values correspond to specific water demands of 2.1 to 3.3 litres per day per cubic metre of raw gas upgrading

capacity. Another technology provider reported water demands of $<1\text{--}2\text{ m}^3/\text{day}$ [35].

Methane recovery rates range between ~ 98.0 and 99.5% (methane loss of $0.5\text{--}2.0\%$) [11, 15, 19]. One technology provider gives warranty values for methane losses of 1% and claims that a decrease down to 0.5% is technically possible [15]. A plant operator reported methane recovery rates at their own plants in the range $98.8\text{--}99.4\%$ [30]. Depending on the ratio between off-gas (before air dosing) and air, it can be advantageous to operate water scrubbers with methane losses of around 1% to be able to operate the subsequent off-gas treatment autothermally.

Even though off-gas may contain CH_4 in concentrations much less than 1% due to dilution with air in the desorption column, significant amounts of CH_4 can be vented with the off-gas. Therefore, legislation might require oxidation by an off-gas-treatment. Because the off-gas normally includes relevant amounts of sulphur and relatively low concentrations of CH_4 , RTO is normally used as off-gas treatment technology in large-scale applications for water scrubbers [33]. For the application of 'catalytic oxidation', precision desulphurization would be necessary in an earlier step because H_2S is a catalyst poison.

Physical absorption by organic solvents

This is a process involving purely physical absorption (physisorption) (Fig. 15.8). In contrast with water scrubbing, an organic reagent (e.g. polyglycol dimethyl ethers) serves as absorption agent in the so-called Selexol[®] process [25, 37]. Compared to water, the organic reagent has increased absorption rates for CO_2 and therefore allows decreased circulation rates of the absorption liquid. Besides biogas upgrading, the process is typically used for the removal of acid gases from natural and synthesis gas [37–39].

A particular feature of this method is the possibility of the parallel absorption of CO_2 , H_2S and H_2O in the scrubbing column [13]; NH_3 can also be absorbed but should be avoided due to the formation of unwanted reaction products in the process [14]. Table 15.2 gives an overview of the solubilities of selected gaseous compounds when upgrading biogas in tetraethylene glycol dimethyl ether (Genosorb[®] 1753) at 25°C [40] (a Genosorb plant is shown in Fig. 15.9). SO_2 is not present in raw biogas. It is only formed afterwards, during the oxidation of H_2S in off-gas treatments. Achievable water dew points after the absorption process are around -20°C related to ambient pressure [14]. Typical CH_4 concentrations in the product gas flow are in the range $93\text{--}98\%$ [13].

Before the untreated gas enters the absorption column, it is compressed to $4\text{--}8\text{ bar}$ [11, 25]. In current applications, an operation pressure of $\sim 6\text{--}7\text{ bar}$ is applied [14]. Downstream cooling of the compressed gas causes



Table 15.2 Solubility in $\text{cm}_n^3/(\text{g bar})$ of selected gases at 25°C in tetraethylene glycol dimethyl ether (Genosorb[®] 1753) [40]

CH_4	CO_2	H_2S	NH_3	O_2	H_2	SO_2
0.2	3.1	21	14.6	0.2	0.03	280

**15.9** Genosorb[®] scrubber plant (Copyright: Fraunhofer IWES).

condensation of water, which can be diverted from the system [13]. The applied operation temperature in the absorption column is $10\text{--}20^\circ\text{C}$ [13]. The design and operation of an organic solvent scrubber are comparable to the water scrubber. As in the water scrubber, no precision desulphurization is usually required. The product gas, dehydrated due to the hygroscopic properties of the absorption agent and desulphurized, leaves the column at its top. Depending on the target specifications of the product gas and the composition of the raw gas, another precision desulphurization step can follow and/or the product gas is dried by adsorption. As in water scrubbers, the saturated washing solution is partly expanded in a flash column. The desorbed gas is recirculated. To achieve reduced methane losses in the system, two flash columns can also be used [14]. Complete desorption is achieved by heat (approx. $40\text{--}80^\circ\text{C}$) and stripping air in the desorption column [11, 14]. Current operation temperatures in desorption columns are in the range $40^\circ\text{C}\text{--}50^\circ\text{C}$ and can be provided by heat uncoupling (heat exchanger/cooling after compression and/or off-gas treatment) without any external heat source [14]. Flow variations in the range $50\text{--}100\%$ of the nominal load are possible [11].

The electricity demand varies from 0.23 to $0.33 \text{ kWh}_{\text{el}}/\text{m}_n^3$ raw biogas [11,

14]. In new plants, electricity consumption can be expected to be in the range $0.23\text{--}0.27 \text{ kWh}_{\text{el}}/\text{m}_n^3$ raw biogas [14]. The heat demand varies from 0.10 to $0.15 \text{ kWh}_{\text{th}}/\text{m}_n^3$ related to raw biogas [14]. As mentioned earlier, this heat quantity can be provided by heat recovery from the upgrading plant [14].

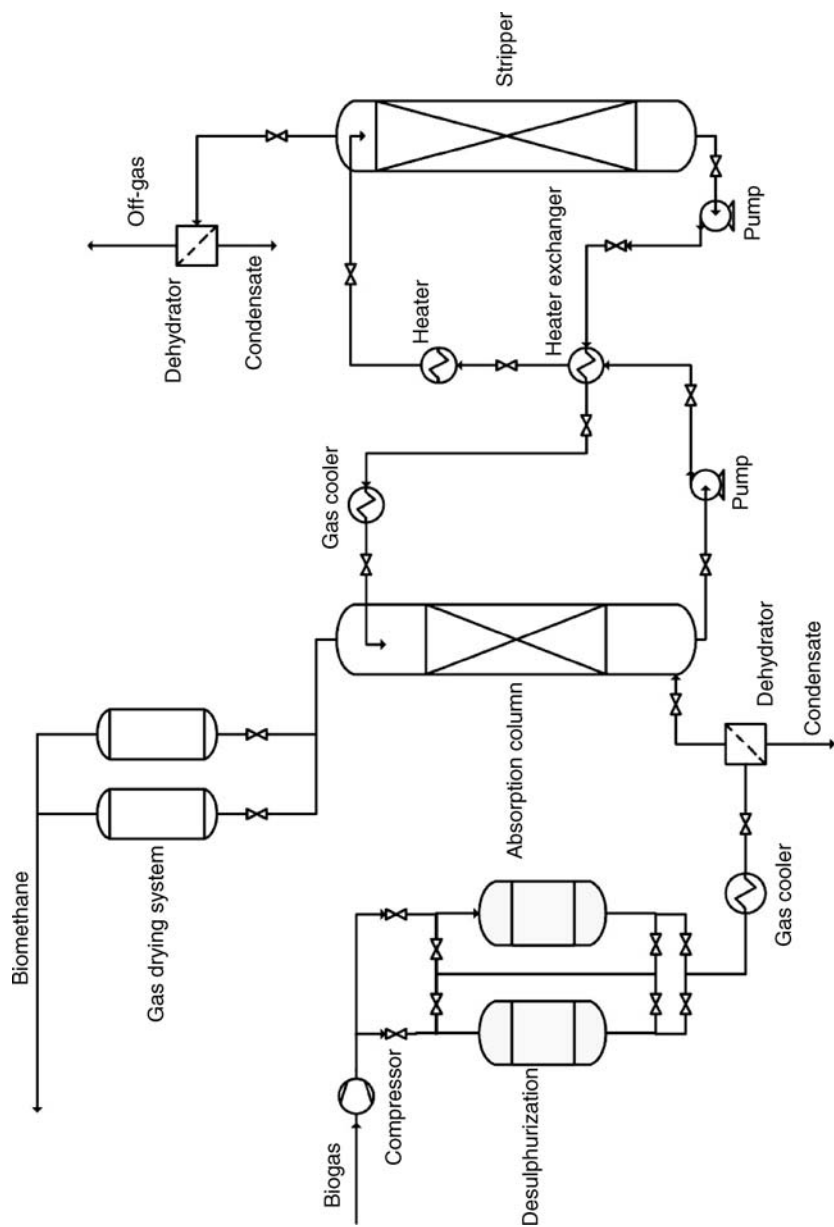
As the off-gas flow includes $1\text{--}4\%$ CH_4 [11] (methane recovery rate of $96\text{--}99\%$) related to the CH_4 flow of the biogas, off-gas gas cleaning can be required. Current warranty values from one technology provider are 1.5% methane loss (methane recovery rate of 98.5%) [14]. Because the off-gas normally contains H_2S , a typical off-gas treatment technology is RTO, which is the standard application in large-scale plants [33]. Flameless oxidation is mostly not recommended because the off-gas contains (due to the addition of air in the desorption column) too low concentrations of CH_4 for autothermal operation.

Chemical absorption by organic solvents

Chemical absorption with organic solvents, often referred to as ‘amine scrubbing’, is a chemisorptive method, meaning that CO_2 and theoretically H_2S are chemically bound to an organic scrubbing agent [8]. Different alkanolamine solutions can be used for the separation of CO_2 in chemical absorption processes and different plant manufacturers use different ethanolamine–water mixtures as absorption agents. Some of the most relevant ones for biogas upgrading are monoethanolamine (MEA), diethanolamine (DEA) and methyldiethanolamine (MDEA) [11, 12, 20]. Chemical absorption by amine solutions has been used since the 1970s for the separation of CO_2 and H_2S in sour gases [20].

Besides CO_2 , H_2S also can be co-absorbed in amine scrubber processes. However, in most applications, a precision desulphurization step is installed before the absorption column to reduce the energy demand for the regeneration process [11]. Typical methane concentrations in the product gas flow are $\sim 99\%$ [12]. Significant amounts of N_2 in the raw gas flow cause decreased product gas qualities because N_2 cannot be absorbed in the process, but this effect is found with nearly all other upgrading methods as well. Furthermore, the entry of O_2 should be avoided because it can create unwanted reactions and degradation of the amine solution [11].

In contrast to purely physical scrubbing, absorption proceeds at almost atmospheric pressure ($\sim 50\text{--}150$ mbar) [17, 20]. Some providers offer systems where the gas is compressed to 4 bar before it enters the absorption column [12]. As mentioned earlier, precision desulphurization normally takes place before the amine solution enters the scrubber [13]. Depending on the used absorption agent (e.g. using an amino acid salt solution) and the manufacturer’s strategy, it can also be omitted at this stage but has to be done in the off-gas flow [20, 41]. The raw gas comes into contact with the



15.10 Process scheme of chemical absorption (using organic solvents) (Copyright: Fraunhofer IWES, 2012).



15.11 Amine scrubber plant (Copyright: Fraunhofer IWES).

amine solution in the absorption column in cross-flow. Unlike in pure physical absorption, there is no flash column. The loaded absorption chemical is regenerated in the desorption column, for which heat is needed. Depending on the manufacturer and thus the used amine solution, temperatures from 106 to 160°C are required in the desorption column (flow temperatures before heat introduction have to be increased in each case) [11, 12, 17, 20]. The product gas, which is saturated with moisture from absorption, must be dried in a subsequent (normally adsorption) process. Controllability in the range 50–100% (compared to nominal load) is possible [11]. One technology provider reports controllabilities in the range 25–100% (compared to nominal load) [41].

Figure 15.10 describes the chemical absorption process (using organic solvents) and an amine scrubber plant is shown in Fig. 15.11.

The electricity demand varies from 0.06 to 0.17 kWh_{el}/m_n³ related to raw biogas [12, 19]. One plant manufacturer currently reaches warranty values for electricity consumption of 0.09 kWh_{el}/m_n³ (for a methane concentration of 65% in the raw biogas) and 0.11 kWh_{el}/m_n³ (for a methane concentration of 55% in raw biogas) – both values correspond to product gas pressures of 50–150 mbar and desorption temperatures of 135–145°C [17]. Another plant manufacturer reports an electricity consumption of 0.17 kWh_{el}/m_n³ raw gas for product gas pressures of 2.5 bar and water temperatures for the desorption process in the range 120–130°C [12]. The heat demand for the desorption process can vary from 0.4 to 0.8 kWh_{th}/m_n³ raw biogas [19]. One plant manufacturer currently reaches warranty values for heat consumption of 0.45 kWh_{th}/m_n³ (for a methane concentration of 65% in raw biogas) and 0.58 kWh_{th}/m_n³ (methane concentration of 55% raw biogas) and desorption

temperatures of 135–145°C [17]. Another plant manufacturer reports typical heat consumptions of 0.55–0.70 kWh_{th}/m_n³ raw biogas [26]. Heat recovery is also possible. One provider states that 20% of the supplied heat can be uncoupled at temperature levels of ~50°C [17].

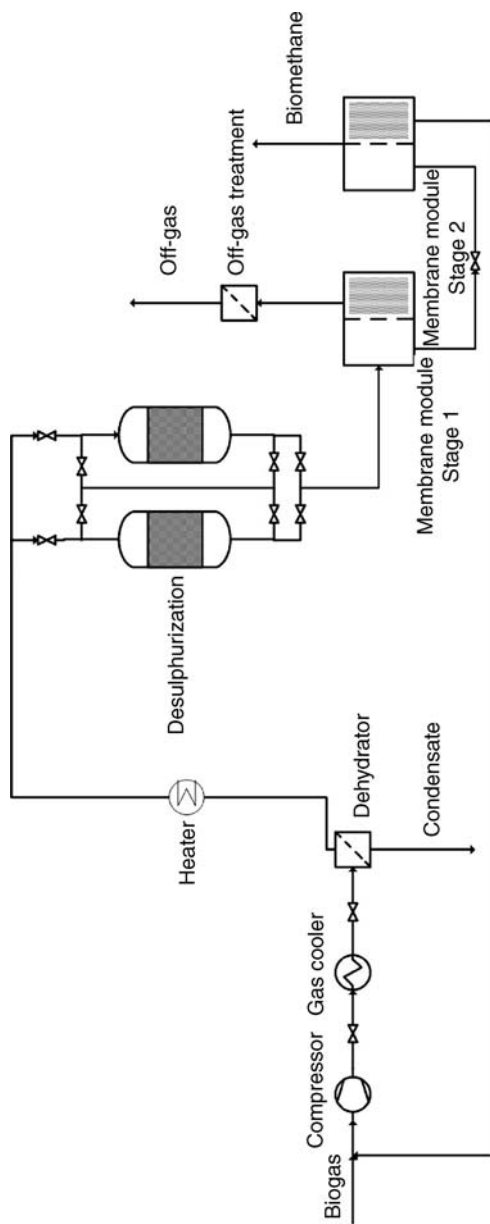
Methane recovery rates are stated to be around 99.9% [11, 17, 26]. Because of very low methane losses in the system (compared to all the other methods), the off-gas does not normally require further treatment.

Membrane separation

Membrane separation, also known as gas permeation, takes advantage of the different permeabilities of gas compounds through polymer membranes [8]. Three different flows can be defined in membrane systems: the feed (raw biogas), the permeate (CO₂-rich gas) and the retentate (CH₄-rich gas). Different partial pressures of respective compounds between the feed and permeate side can be defined as the driving force of the system [42]. Increased pressures on the feed side and decreased pressures on the permeate side cause high flux rates [42]. Candidate polymers include cellulose acetate and aromatic polyimides [13], which have high permeabilities of CO₂, H₂O, NH₃ and H₂S compared to CH₄ [13]. Permeabilities for N₂ in particular but also for O₂, are significantly lower [43]. An essential parameter for economic operation of membrane systems for biogas upgrading (separation CO₂/CH₄) is the selectivity of these two gas compounds. For polyimide/polyaramide membranes, CO₂/CH₄ selectivities range between 20 and 25 [44]. In the past, CO₂/CH₄ selectivities had been ~20 but there are now membrane materials available with selectivities of ~50 [43]. As of 2012, membrane materials with CO₂/CH₄ selectivities of ~70 were in the testing phase [43].

To extend the life of the membranes and obtain optimum separation, the raw gas is dried and precision desulphurized, and dust and aerosols are separated, before the gas enters the membrane [8]. The biogas is compressed (depending on the manufacturer) to 7–20 bar (in systems of the 1980s and 1990s, pressures greater than 20 bar were used) and precision desulphurized either before or after compression; it then enters the membrane modules [7, 18, 21, 45]. Pressure losses in the system can be assumed to be ~1 bar [18]. Inside the membrane module, the CO₂ permeates the membrane while the majority of CH₄ is not permitted to pass. Most practical applications use processes involving at least two-stage systems (see Fig. 15.12) [13, 42]. The permeate flow still contains some methane so that the off-gas flow (e.g. of the second stage) is recirculated or is passed through an additional stage [13, 42]. Because membrane upgrading plants consist of a number of single membrane modules, these systems show excellent part load behaviours.

Electricity demand can vary from 0.18 to 0.35 kWh_{el}/m_n³ raw biogas



15.12 Process scheme of a two-stage membrane separation system for biogas upgrading (Copyright: Fraunhofer IWES, 2012).



15.13 Membrane separation plant (Copyright: Fraunhofer IWES).

depending on applied operation pressures, recirculation volume flows and membrane qualities [18, 19, 21, 45]. In new systems, specific energy consumptions are significantly lower than the upper value of $0.35 \text{ kWh}_{\text{el}}/\text{m}_n^3$. One membrane provider states specific electricity demands of $<0.2 \text{ kWh}_{\text{el}}/\text{m}_n^3$ related to raw biogas upgrading capacity (for operation pressures of 10–20 bar) [21]. A plant provider has stated specific electricity demands in the range of $0.29\text{--}0.35 \text{ kWh}_{\text{el}}/\text{m}_n^3$ depending on raw gas constitution and methane recovery rate (related to upgraded biomethane with a CH_4 concentration of 97%) [43]. In a large-scale operation plant located in Germany, a specific electricity consumption of $0.20 \text{ kWh}_{\text{el}}/\text{m}_n^3$ raw biogas has been reached [18].

Methane recovery rates stated in the literature range from 85 to 99% (methane losses of 1–15%) [19, 21]. In the past, economic methane recovery rates could be expected in the range 95–96% [18]. Increased yields were possible, but led to increased recirculation rates and therefore to increased electricity consumption.

Because the off-gas flow contains significant amounts of CH_4 it can be necessary to oxidize it in an off-gas treatment step. Suitable treatment methods are comparable to those of the PSA systems described earlier. A membrane separation plant is shown in Fig. 15.13.

Cryogenic upgrading

Cryogenic upgrading uses the effect of different boiling points of methane (-161°C) and sublimation points of carbon dioxide (-78.48°C) [46]. Depending on the temperature level in the process, theoretically other gas

components can also be separated in a cryogenic process. Using the example of the practice of one manufacturer, the following steps take place [13].

- First a dew point decrease to 6°C takes place. At this temperature, H₂S and siloxanes can be (partly) removed by catalytic adsorption.
- After this pretreatment, the raw gas is compressed up to 18–25 bar.
- The temperature is then decreased to –25°C. At this temperature, the gas is dried and possible remaining siloxanes may also be condensed.
- The final step of desulphurization (polishing) takes place.
- Temperature decrease to –50 to –59°C causes liquefaction of the CO₂, which is then removed from the system.

A methane loss of 0.1–1% can be expected [19]. In 2008, one manufacturer expected a methane loss of <0.5% [13]. According to new information (2012), methane losses are limited to 2% [24]. The demand for electricity has been reported to be 0.18–0.25 kWh_{el}/m_n³ related to raw biogas [13]. Because the off-gas contains significant amounts of CH₄, emissions reductions in the off-gas flow may be necessary.

15.3.3 Off-gas treatment

Depending on the off-gas composition, one or several off-gas treatment steps may be needed. The most relevant contaminants are CH₄ and H₂S respectively sulphur oxides SO_x. Depending on particular loads and/or concentrations of these contaminants, respective national legal requirements can demand degradation or separation of these substances. As an example of possible legal requirements, Table 15.3 shows limitations of emissions according to German ‘technical instructions on air quality control’ (TA Luft 2002); these technical instructions are also partly applied in other European countries [47].

Hydrogen sulphide (H₂S) will occur in concentrations greater than 5 mg/m_n³ in the unoxidized off-gas if no preliminary removal has been carried out in the raw gas flow; this is normally what can be expected using water scrubbers or Genosorb[®] scrubbers for biogas upgrading. If these off-gas flows, containing relevant concentrations on H₂S, are oxidized, SO_x are

Table 15.3 Emission limits according to German TA Luft 2002 for relevant substances in the off-gas of biogas upgrading plants [47]

	Mass flow (g/h)	Mass concentration (mg/m ³)	Comments
CH ₄	500	<50	Indicated as total carbon
H ₂ S	15	<3	
SO _x	1800	<350	Indicated as sulphur dioxide

formed. Depending on the SO_x load and potential emission requirements, an additional SO_x cleaning step might be required. For H_2S reduction in off-gas flows, activated carbon filters are usually used. If there is a demand for reduction of SO_x in off-gas flows, basic (lye) scrubbers (using, for example, NaOH as absorbent) are normally used [33].

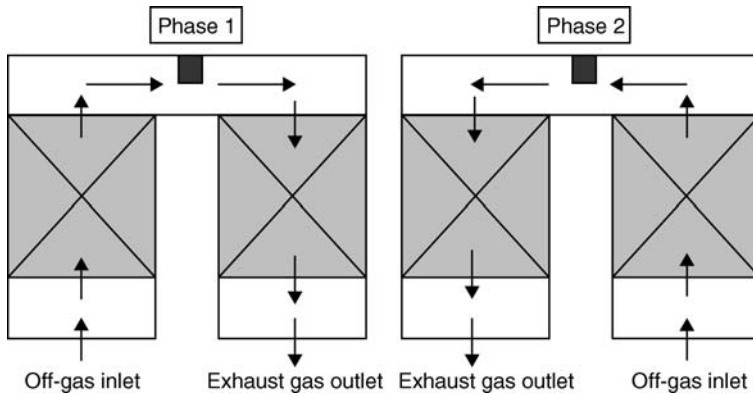
Depending on the applied biogas upgrading method and its operational mode, methane loads in the off-gas flow can vary from 0.1% up to ~15% (see Table 15.1) of the concentration in the raw biogas at the inlet of the upgrading plant. In this context two terms have to be defined.

- Methane loss or methane slip is the ratio of the quantity of methane that does not appear in the product gas to the quantity of methane in the raw biogas at the inlet to the upgrading plant [8].
- Methane emissions to the atmosphere are the ratio of the quantity of methane that is emitted unoxidized to the atmosphere to the quantity of methane in the raw biogas at the inlet to the biogas upgrading plant [8].

For degradation of CH_4 in the off-gas, the methods of practical relevance are [33]

- regenerative thermal oxidation (RTO)
- catalytic oxidation
- flameless oxidation (in Flox[®] burners)
- co-firing in combustion engines (e.g. micro turbines).

Regenerative thermal oxidation (RTO) is a suitable treatment method for off-gas flows with low methane concentrations [8] and is thus mostly applied in off-gas streams of water scrubbers and Genosorb[®] scrubbers [33]. In the future, it may also become an advantageous treatment method for off-gases from PSA and membrane systems, provided that sufficiently low methane losses (and therefore low methane concentrations in the off-gas) will be reached in those processes. Autothermal operation (without co-firing of natural gas, liquefied petroleum gas (LPG) or raw biogas) is already possible with methane concentrations of 0.2%_{vol}, which is equivalent to 1.3 g CH_4/m_n^3 [48]. However, for the start-up phase, heating with higher calorific gases is needed [9]. Compared with other off-gas treatment methods, RTO can be made resistant to corrosive media such as H_2S and its degradation products [9]. The operation temperature inside the RTO system is ~800°C [48]. To guarantee complete oxidation, an oxygen concentration of minimum 10%_{vol} has to be ensured. To ensure low heat losses, heat is stored in ceramic materials (the shaded boxes in Fig. 15.14) and the flow direction is switched continuously. As illustrated in Fig. 15.14, in phase 1 the ceramic bed on the left-hand side preheats the gas before oxidation takes place. Before the exhaust gas leaves the second chamber, this hot gas heats the ceramic bed on the right-hand side. Phase 2 illustrates the process after the



15.14 Illustration of a two-chamber regenerative thermal oxidation unity (Copyright: Fraunhofer IWES, 2012).



15.15 Regenerative thermal oxidation system for off-gas treatment at a biogas upgrading plant (Copyright: Fraunhofer IWES).

flow direction is switched [48]. Figure 15.15 shows a RTO system for off-gas treatment at a biogas upgrading plant.

Catalytic oxidation is another off-gas treatment method, which is of particular relevance to off-gas streams of PSA systems [33]. Because impurities such as H_2S act as a catalyst poison, there are increased requirements on the gas composition compared with RTO [48]. Platinum and palladium are usually used as catalyst materials, but cobalt may also be used [9, 48]. Autothermal operation is already possible with methane concentrations of $0.4\%_{\text{Vol}}$, equal to $2.7 \text{ g CH}_4/\text{m}_n^3$ [48], but the start-up

phase requires heating with higher calorific gases or electricity [9]. The operation temperature inside the reaction chamber is only $\sim 400^{\circ}\text{C}$ because of the reduced activation energy. To guarantee complete oxidation, an increased oxygen concentration of 2%_{vol} (compared with stoichiometric) has to be ensured [48].

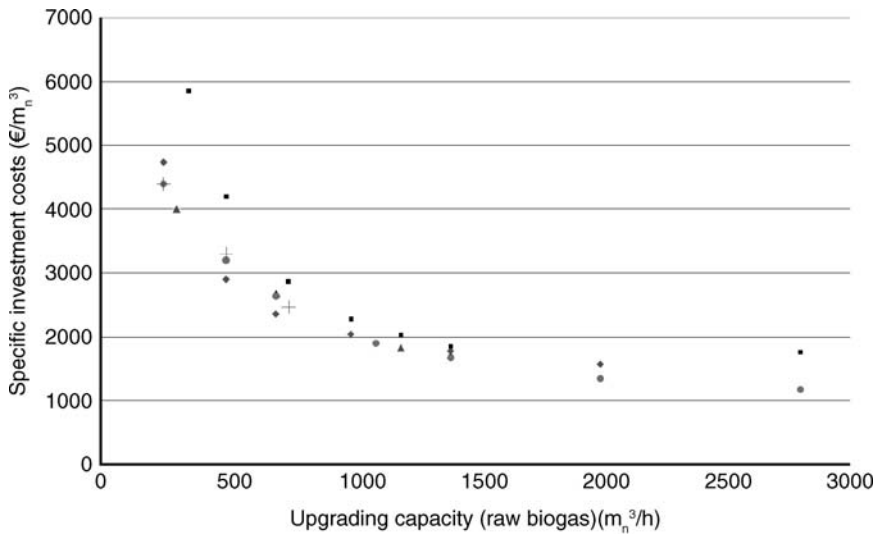
Lean gas burners such as flameless oxidation processes have practical relevance, especially for off-gas streams of PSA systems and membrane separations [33]. This is a suitable technology for high methane concentrations and if there is sufficient heat demand (e.g. for the provision of digester heat). Autothermal operation is possible with methane concentrations of 4–5%_{vol} ($27\text{--}34\text{ g CH}_4/\text{m}_n^3$) [9, 48, 49]. Because most biogas upgrading methods have much lower CH_4 concentrations in the off-gas, either methane slip has to be set intentionally high or a dosing of high calorific gas (e.g. raw biogas) is necessary [8]. The operation temperature of $\sim 900^{\circ}\text{C}$ is significantly higher than for the other methods described above [49]. With this high process temperature it is appropriate to preheat air and lean gas to temperature levels of $\sim 500^{\circ}\text{C}$ [49]. The exhaust gas leaves the plant at a temperature of $\sim 600^{\circ}\text{C}$ [49] and therefore this method is suitable for the provision of process heat or external heat utilization.

Oxidation of off-gas by co-incineration in combustion engines or boilers is also possible and has been applied in early installations in the USA [2]. However, utilization of pure off-gas is not possible so the off-gas must be mixed with a higher calorific gas (e.g. raw biogas). The most suitable modules for this method are micro turbines because of the lowest required calorific value of $3.8\text{ kWh}/\text{m}_n^3$ (Hs) [9]. This means (if only methane is the energy carrier as fuel) that a minimum methane concentration of 35%_{vol} has to be reached at the fuel inlet of the micro turbine.

15.4 Costs of biogas upgrading

Because the cost of biogas upgrading is the decisive criterion in a project, relevant financial parameters are now discussed. It is important to note that all data stated here should not be used alone as decision criterion within a project.

Figure 15.16 shows specific investment costs as a function of raw biogas upgrading capacity for five upgrading technologies. The costs do not include planning, permission or other further construction costs. All costs are based on price indications of current plant generations provided by manufacturers [14–17, 45]. These costs are therefore not representative for the respective technologies but can be considered as indications only. All costs except those for amine scrubbers include an off-gas treatment step for CH_4 degradation. This means that for some technologies, the specific investment



▪ PSA ▲ Water scrubber • Genosorb® scrubber ♦ Amine scrubber + Membrane

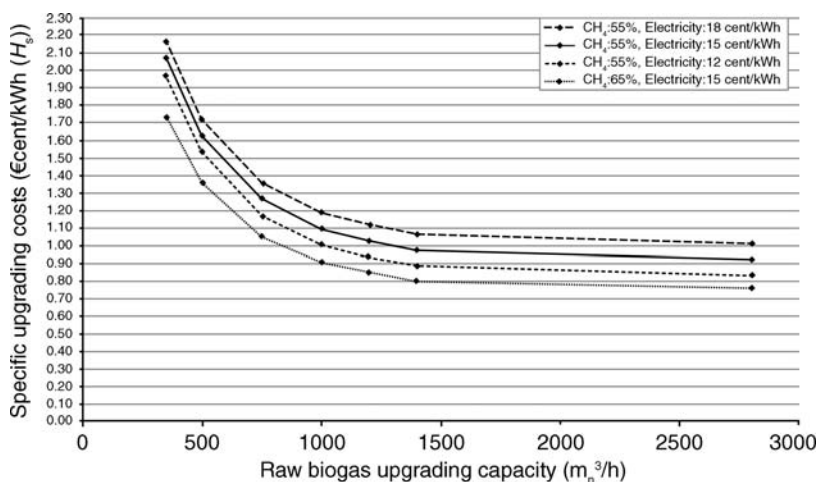
15.16 Specific investment costs in € per m_n^3 raw gas upgrading capacity of five biogas upgrading methods based on [14–17, 45] (Copyright: Fraunhofer IWES, 2012).

costs will be decreased if no off-gas treatment is included. Analysis of Fig. 15.16 would suggest

- significant cost degression for capacities increasing from 250 to 500 m_n^3/h
- further cost degression for a capacity increase from 500 to 1000 m_n^3/h
- marginal degressions for increases above 1000 m_n^3/h raw gas upgrading capacity
- specific investment costs for the different methods tend to be comparable for all technologies, especially in the range 700–1400 m_n^3/h .

Subsequent specific upgrading costs for these five different methods are discussed using the following framework conditions and assumptions.

- Investment and maintenance (as full maintenance contract) costs based on price indications of current plant generations of technology providers [14–17, 45].
- Interest rate of 5%.
- Costs for planning, permission and further construction costs; 10% related to investment costs.
- Operating time of 15 years.
- Costs for insurance; 0.5% related to investment costs according to [50].
- Plant availability of 96% (8410 h/year).



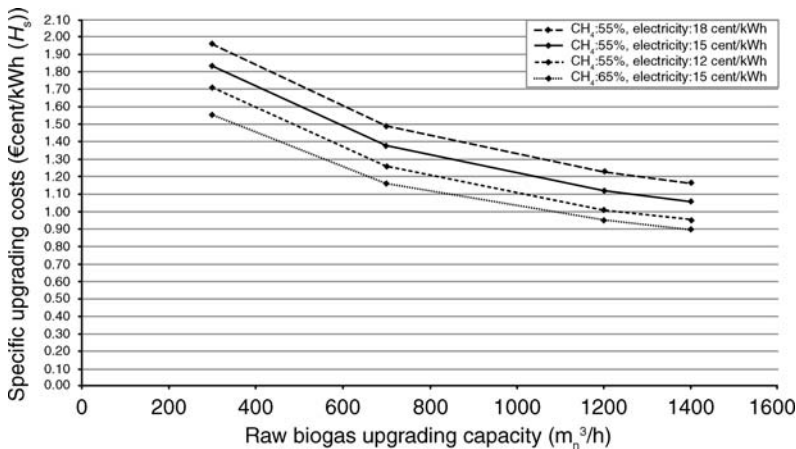
15.17 Specific biogas upgrading costs for PSA based on price indications and warranty values according to [16] (Copyright: Fraunhofer IWES, 2012).

- Specific energy consumptions (with respect to 55% and 65% methane concentrations in the raw gas flow) and methane recovery rates based on warranty values [14–17, 45].
- Personal costs for each method and plant size of 35 €/h, 1 h/day.
- Precision desulphurization (if required): H_2S reduction by 100 ppm, 5€ per m_n^3 raw gas upgrading capacity and year (includes costs for activated carbon [51], costs for the disposal of loaded coal as hazardous waste and carrying costs [52]).

Variations are made for methane concentrations in the raw biogas of 55% and 65%, depending on the upgrading method for electricity (12–18 cent/kWh_{el}) and heat costs (3–5 cent/kWh_{th}). Costs for further treatment steps (e.g. separation of siloxanes or NH_3) are not considered. All values are based on full operation mode; part load operation is not considered. The sale of low-temperature heat provided by heat uncoupling of compressor cooling, off-gas treatment or cooling of absorption solution is also not considered.

Figure 15.17 shows specific upgrading costs for raw gas upgrading capacities in the range 350–2800 m_n^3/h for a PSA system. Precision desulphurization has been considered. The calculations are based on specific electricity demands of 0.17 kWh_{el}/ m_n^3 (65% CH_4) and 0.18 kWh_{el}/ m_n^3 (55% CH_4) both related to raw gas, methane recovery rates of 98.5% and product gas pressures of 2 bar.

Figure 15.18 shows specific upgrading costs for raw gas upgrading capacities of 300–1400 m_n^3/h for a water scrubber system. Precision

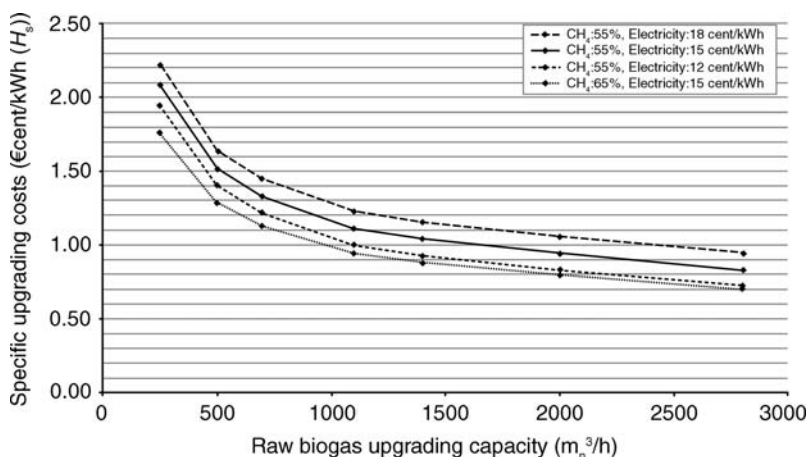


15.18 Specific biogas upgrading costs for water scrubber based on price indications and warranty values according to [15] (Copyright: Fraunhofer IWES, 2012).

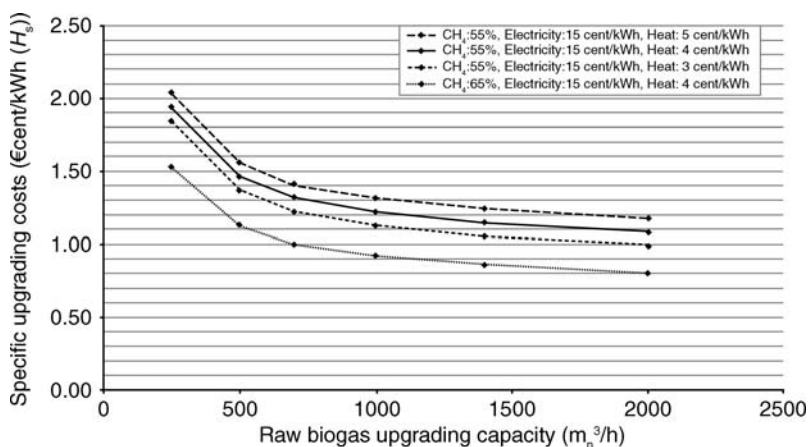
desulphurization has not been considered. Calculations are based on specific electricity demands from $0.22 \text{ kWh}_{\text{el}}/\text{m}_n^3$ ($1400 \text{ m}_n^3/\text{h}$ upgrading capacity) to $0.25 \text{ kWh}_{\text{el}}/\text{m}_n^3$ ($300 \text{ m}_n^3/\text{h}$ upgrading capacity), both related to raw biogas, and independent of CH_4 concentrations in the raw gas flow. Furthermore, costs are related to methane recovery rates of 99.0%, product gas pressures of 5 bar and average ambient temperatures of 10°C . Water consumptions were assumed to be $1 \text{ m}^3/\text{day}$ for small and $3 \text{ m}^3/\text{day}$ for large upgrading capacities, using costs of 5 €/m^3 including wastewater charge.

Figure 15.19 shows specific upgrading costs for raw gas upgrading capacities in the range $250\text{--}2800 \text{ m}_n^3/\text{h}$ for a Genosorb[®] scrubber system. Precision desulphurization has not been considered. Calculations are based on specific electricity demands of $0.23 \text{ kWh}_{\text{el}}/\text{m}_n^3$ ($500\text{--}2800 \text{ m}_n^3/\text{h}$ upgrading capacity) and $0.27 \text{ kWh}_{\text{el}}/\text{m}_n^3$ ($250 \text{ m}_n^3/\text{h}$ upgrading capacity), both related to raw biogas and independent of CH_4 concentrations in the raw gas flow. Costs are related to methane recovery rates of 98.5% and product gas pressures of 6.5 bar. Heat for desorption is assumed to be provided within the system without any external heat supply.

Figure 15.20 shows specific upgrading costs for raw gas upgrading capacities in the range $250\text{--}2000 \text{ m}_n^3/\text{h}$ for an amine scrubber system. Precision desulphurization has been considered. Calculations are based on specific electricity demands of $0.09 \text{ kWh}_{\text{el}}/\text{m}_n^3$ (65% CH_4 in raw gas flow) and $0.11 \text{ kWh}_{\text{el}}/\text{m}_n^3$ (55% CH_4 in raw gas flow), as well as specific heat demands of $0.45 \text{ kWh}_{\text{th}}/\text{m}_n^3$ (65% CH_4 in raw gas flow) and $0.58 \text{ kWh}_{\text{th}}/\text{m}_n^3$ (55% CH_4 in raw gas flow), all values related to raw biogas. Furthermore,



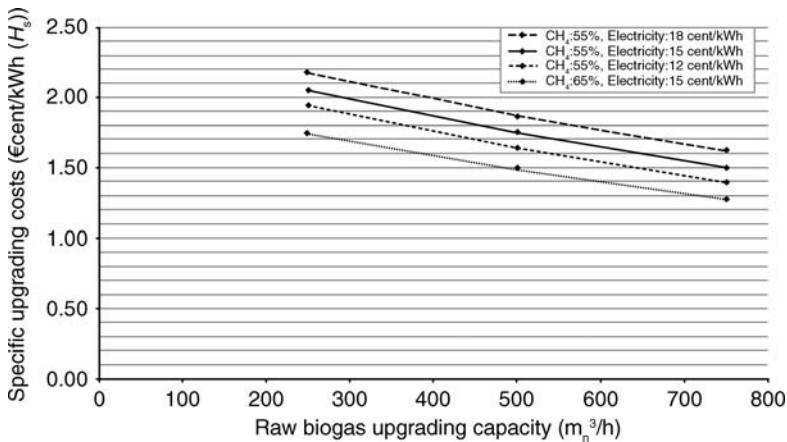
15.19 Specific biogas upgrading costs for Genosorb® scrubbers based on price indications and warranty values according to [14] (Copyright: Fraunhofer IWES, 2012).



15.20 Specific biogas upgrading costs for amine scrubbers based on price indications and warranty values according to [17] (Copyright: Fraunhofer IWES, 2012).

methane recovery rates of 99.9% and product gas pressures of 1.15 bar are assumed.

Figure 15.21 shows specific upgrading costs for raw gas upgrading capacities in the range 250–750 m_n^3/h for a membrane separation system. Precision desulphurization has been considered. Calculations are based on specific electricity demands of $0.35 \text{ kWh}_{el}/m_n^3$ (65% CH_4 in raw gas flow) and $0.40 \text{ kWh}_{el}/m_n^3$ (55% CH_4 in raw gas flow), both values related to



15.21 Specific biogas upgrading costs for a membrane separation system based on price indications and warranty values according to [45] (Copyright: Fraunhofer IWES, 2012).

product gas (CH_4 concentration 97%). Methane recovery rates of 95.0% and product gas pressures of 7 bar are assumed.

All specific costs stated in this chapter are related to product gas (H_s = upper heating value). In all cases, the specific upgrading costs of higher calorific raw gases are lower. This is primarily due to increased energy outputs because overall costs are related to higher energy levels. However, it can be partly also influenced by increased efficiencies (decreased energy demand per energy output) because specific energy demands can be decreased using higher calorific raw gases.

Furthermore, the influence of energy costs will be discussed (all variations are related to raw gas with 55% methane). As a ‘base scenario’, electricity costs of 0.15 €/kWh_{el} and heat costs of 0.04 €/kWh_{th} were assumed. Apart from the amine scrubber costs, electricity costs were varied by plus and minus 20% (absolute by 0.03 €/kWh_{el}) compared to the base scenario. Depending on the upgrading method and plant size, this corresponds to increased or decreased specific upgrading costs of $0.08\text{--}0.13 \text{ cent/kWh}_{H_s}$. For amine scrubbers, heat costs were varied by plus and minus 25% (absolute by 0.01 €/kWh_{th}) compared to the base scenario. This corresponds to increased or decreased specific upgrading costs of $0.10 \text{ cent/kWh}_{H_s}$. The same effects would apply if energy consumptions were increased or decreased by the above presumed percentage rates. Basically, all results always have to be regarded together with pressure levels of the product gases and the framework conditions described above.

Another important parameter for cost-efficient biomethane provision is the operational availability and nominal load operation. Nominal load operation of upgrading plants not only depends on high availabilities of the

upgrading plant itself, but the continuous provision of nominal raw gas flows and high availabilities of post-processes (e.g. grid injection station or filling station) also have a significant influence on nominal load operations of upgrading plants.

Short downtime, good functionality of equipment to enable operation of the plant at rated load and the continuous availability of sufficient raw gas are decisive criteria for the high availability of a biogas upgrading plant. Quick response times for essential maintenance and thus good service networks supported by technology providers are vital. Furthermore, many plant suppliers offer remote monitoring of the treatment plant. The advantage of this is that, when operation is disrupted, the manufacturer's specialists can find the fault directly and – depending on the type of fault – take necessary remedial action immediately. This avoids delays such as when a service technician must travel a long distance to the site.

15.5 Conclusion

Many of today's methods for CO_2/CH_4 separation are based on other industrial applications that have been in service for several decades. There are several methods available, as described in this chapter, that can be seen as state-of-the-art for biogas upgrading. Within recent years several developments have led to decreased energy consumption, increased recovery rates and reduced methane emissions to the atmosphere. The current trends show that, depending on the upgrading method, technology providers are trying to decrease specific electricity demands (but often by accepting reduced product gas pressures), decrease required temperature levels for desorption processes (amine scrubbers), develop membranes with higher selectivities for CO_2/CH_4 , advance technologies for the provision of liquefied biomethane and combine technologies (e.g. membrane and cryogenic processes). These developments indicate that, in the future, more efficient and also new technologies will be available.

Depending on price levels (especially for natural gas), available infrastructure and national legal framework conditions, biomethane can become one of the most promising renewable energy carriers. The flexibilities of biomethane with respect to storage capability, local and temporal decoupling of production and utilization as well as applicability in several utilization paths form, in combination, the unique feature of biomethane.

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Biomethane injection into natural gas networks

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Abstract: Biomethane is a flexible and easily storable fuel that can be used wherever natural gas is used without the need to change any settings on equipment designed to use natural gas. In regions where a natural gas grid already exists, there is a ready-made system for the distribution of biomethane. This chapter briefly introduces: the legal framework and technical standards of biomethane feed-in into the gas network in Germany; the different subsidy schemes and reliefs to encourage biomethane production or utilization; and the different available options for biomethane feed-in and feed-in facilities. The chapter also looks at one of the most challenging aspects of biomethane feed-in – costs and energy efficiency – and outlines several options for improvement.

Key words: biomethane, natural gas grid, grid injection, gas injection regulation, gas conditioning.

16.1 Introduction

Biomethane is the only mature renewable energy vector that is currently directly applicable in all of the sectors – electricity, heat and transport fuel. It is easily storable and is an ideal option for flexible power generation in cogeneration plants. Biogas, from which biomethane is most commonly obtained, and biomethane are thus valuable contributors to the energy and transport fuels markets and can be readily integrated into renewable energy systems (Urban, 2010). The storage capacity of the natural gas grid may be utilized and heat demand may be satisfied independently of the location and time of biogas production. The utilization of biomethane in cogeneration

plants and as fuel in natural gas powered vehicles leads to a particularly high potential contribution to greenhouse gas emission reduction.

Germany has by far the highest number of gas upgrading and injection plants as well as the highest biomethane production capacity in Europe. Over a period of several years Germany has introduced clear legal guidelines and support mechanisms for biomethane. This chapter therefore focuses on the German situation as an example.

16.2 Technical and legal conditions of biomethane feed-in in Germany

In the last few years, Germany has instigated significant legislative changes, improved the general legal framework conditions and encouraged the use of biomethane for energy production.

The cogeneration of electricity and heat from biomethane in Germany is subsidized under the Renewable Energy Sources Act (EEG), the latest revision of which was in 2012 (EEG, 2012). According to the EEG, producers of electricity from biogas and biomethane fed into the power network receive a feed-in tariff over a period of 20 years for the electricity fed into the network. The so-called 'gas separation rule', adopted by the EEG in 2004, allowed a decoupling of biogas production and use in terms of time and place and created the preconditions for the efficient and ecologically sound use of biogas. By definition, any consumption of natural gas from the gas network is regarded as renewable biomethane if, by the end of a calendar year, the same volume of biogas has been fed into the gas network at another location within Germany. To build customer confidence, the EEG and the Renewable Energy Heat Act (known as the EEWärmeG) (EEWärmeG, 2008) commit biomethane suppliers to apply a green gas certification system (based on mass balancing) to guarantee the origin of the biomethane and to avoid double counting.

The Gas Network Access Ordinance (*Gasnetzzugangsverordnung* (GasNZV) regulates the injection and transportation of gas; it was revised in 2008 and completely redrafted in 2010 (GasNZV, 2010). The EEWärmeG accepts the use of biomethane in highly efficient cogeneration systems as a contribution to meet the mandatory share of energy from renewable sources in new dwellings. In addition, investment subsidies for biogas upgrading plants with capacities up to 350 m³/h are available under the Market Incentive Program (in German, *Marktanreizprogramm* (MAP)) (Dena, 2012a). In the fuels sector, biomethane can be included as a biofuel for the purposes of meeting the biofuels quota or is eligible for energy tax exemption. The revisions of the GasNZV and the EEG in 2008 improved the conditions for investment and, as a result, increased the number of

biogas upgrading plants. The number of plants feeding biomethane into the gas network has increased rapidly (more than doubled in the period 2009 to 2011) since these changes were implemented.

16.2.1 Special regulations for gas network access of biogas plants

In 2005, the Gas Network Access Ordinance (GasNZV) introduced a special provision for biogas, regulating access to local distribution networks, setting a priority for biogas transport and outlining responsibility with regard to necessary expenditures. It is important to note that legislation in Germany uses the word biogas to mean gas after upgrading to a quality often referred to elsewhere as biomethane.

Following a decision by the German government in 2008, a separate section – Section 11a on Special regulation for the injection of biogas into the natural gas network – was included in the GasNZV. In seven new paragraphs, the special regulations already in effect were defined in detail for biogas and made grid access conditions for biogas suppliers far easier. The most important financial factor was the adoption of a clause regulating cost sharing between the gas provider and the grid operator, as well as payment for avoided cost of the mains operation by the network operator. In return, network operators are allowed to recover all costs by increasing the gas network fees paid by customers.

A new GasNZV and the amended Ordinance on Gas Network Tariffs (*Gasnetzentgeltverordnung* (GasNEV)) (Dena, 2012b) entered into effect in September 2010. The regulation easements were increased again. The most important provisions are now explained in more detail.

Network operators on all pressure levels in the grid are obliged to grant priority network access for biomethane. Furthermore, they should grant preference to biomethane transport clients when feeding and withdrawal contracts are concluded, as long as these gases are compatible and meet the appropriate quality standards for the network. The network operator may only deny feed-in if injection is technically not possible or economically not feasible. The feed-in of biogas cannot be denied by the network operator under the premise of an existing capacity shortage. At the same time, the network operator is obliged to take all necessary and economically reasonable measures to ensure access to the net throughout the year and to optimize the admittance capacity. In order to avoid delays in the network access process, the 2010 revision of the GasNZV includes ‘realization roadmaps’, which are to be designed and agreed upon by the network operator and the biomethane supplier and are to be presented to the Federal Network Agency (FNA; *Bundesnetzagentur* in German), together with the

network access contract. The FNA for electricity, gas, telecommunications, post and railways is a federal authority within the responsibility of the German Federal Ministry of Economics and Technology. The FNA's task is to provide, by liberalization and deregulation, for the further development of the electricity, gas, telecommunications, post and railway infrastructure markets. The roadmap lists all relevant steps to making the final network connection.

The network access costs are split between the network operator and the biomethane supplier: the former pays 75% of the overall capital expenditures of the connecting pipeline (up to 10 km), the gas pressure metering plant, the compressor and the calibrated measurement unit; the latter pays 25%. The cost to the biomethane supplier for the installation of network access and the first kilometer of the connection pipe is limited to €250,000 (in 2012).

The network operator has to provide availability of the net at least 96% of the time. The network operator is the owner of the network connection and is responsible for the costs of maintenance and operation. Article 36 of GasNZV defines the quality of biomethane based on the technical regulations G 260 (DVGW, 2008a) and G 262 (DVGW, 2008b) of the German Technical and Scientific Association for Gas and Water (DVGW) (see Table 16.1). GasNZV also defines the maximum loss of biogas and emissions to the atmosphere as not more than 0.2% of the raw gas (v/v). This value has to be guaranteed by an official certificate. GasNZV also regulates the account for biogas grid injection and utilization, i.e. the balance between gas input and gas output. For transport system operators of natural gas, the balance between feed-in and utilization has to be balanced within an hourly tolerance of $\pm 10\%$; in the case of biomethane the tolerance is up to 25%. The total balance has to be achieved on a 12-month term. This is important because, in summer, the input of biomethane is usually far higher than the output.

There is a charge for this flexibility of 0.1 cent/kWh to be paid to the network operator. On the other hand, according to GasNEV (Dena, 2012b), the biomethane supplier receives an avoided mains fee charge of 0.7 cent/kWh of biomethane fed into the network.

16.2.2 Technical standards and rules of technology

In agreement with German law, the DVGW sets technical rules and standards within the scope of public natural gas transport, storage and consumption. The technical quality requirements and the permitted methods of feeding biomethane into the public gas network are defined in DVGW G 260 and G 262. The biomethane supplier has to ensure the gas quality (either H (high) or L (low) natural gas quality), whereas the grid

Table 16.1 Overview of DVGW technical regulations (non-exhaustive)

DVGW regulation (date published)	Description
G 260 (January 2000, May 2008, new draft January 2012)	Gas properties; GasNZV mentions that the technical regulation G 260 (January 2000) has to be applied
G 262 (November 2004, September 2011)	Utilization of gases from regenerative sources in the public gas supply, GasNZV ensures that G 262 (November 2004) has to be applied
VP 265 (April 2008)	Preliminary test specification for 'Biogas upgrading plants and injection into the natural gas grid – Part 1: Gases generated by AD; design, construction, installation, testing and commissioning'
G 265-2 (January 2012)	'Biogas upgrading plants and injection into the natural gas grid – Part 2: Gases generated by AD; operation and maintenance'
G 280 (August 2004, new draft November 2010)	Gas odorization
G 290 (December 2011)	Compression and injection of biogas or natural gas from a low-pressure grid into an upstream medium- or high-pressure grid
G 415 (June 2011)	Guidelines for planning, construction and operation of biogas pipelines
G 486 (August 1992)	Factors for real gases and natural gas compressibility figures – calculation and application
G 488 (July 1999), new draft November 2008)	Equipment for the determination of gas properties – design, construction and operation
G 493-1 (draft December 2011)	Qualification criteria for designers and manufacturers of gas pressure regulation, metering and biogas feed-in equipment
G 685 (November 2008)	Procedures to determine data for gas accounting
G 1030 (December 2010)	Requirements on the qualification and organization of operators of facilities for production, transmission, upgrading, conditioning and feed-in of biogas
G 2000 (December 2011)	Minimum requirements in respect of interoperability and connection to gas supply networks

operator has to ensure compliance with the combustion characteristics (e.g. Wobbe index, heating value and relative density; see Section 16.10 for a glossary) with the distributed natural gas within local gas network.

Further regulations of the DVGW, as well as DIN standards, have to be followed when feeding biomethane into supraregional (defined in Section 16.3) transport pipelines. Standards DIN 51624 (DIN, 2008) and CBP 2005-

001/02 (CBP, 2005) will then apply. Technical regulations of the DVGW dealing with safety and interoperability standards or the design, installation and operation of biogas network connection facilities are listed in Table 16.1.

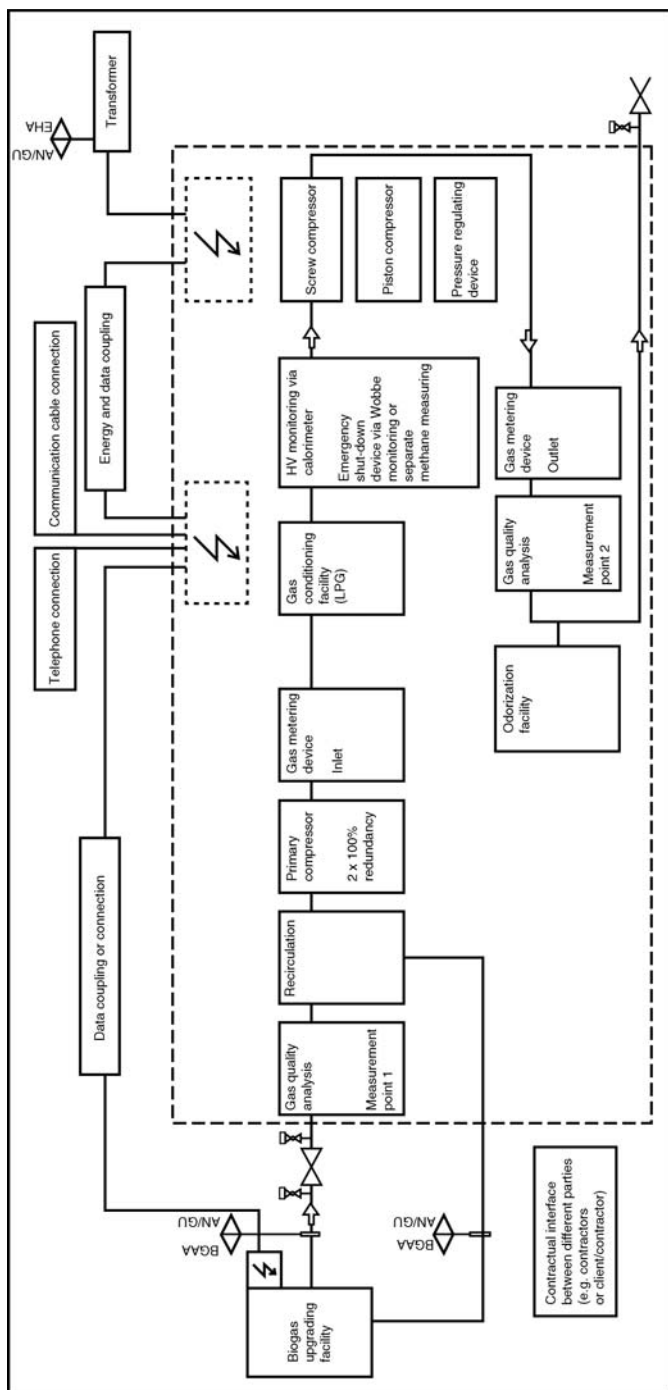
16.3 Design and operation of injection utilities

The design and operation of biogas injection equipment depend on the operating conditions of the natural gas grid (pressure, gas composition and combustion characteristics of the locally distributed natural gas, length of the pipeline connecting to the supply network) and the type of biogas upgrading facility. The design of an injection facility is primarily dependent on the natural gas grid; that is, if it is a distribution grid (low pressure of 30–100 mbar), a regional distribution network (medium pressure of 4–16 bar) or a supra-regional gas transmission network (high pressure, between 32 and 120 bar).

16.3.1 Basic design of a biomethane gas feed-in station

The feed-in station is the link between the upgrading facility and the public gas network (Fig. 16.1). At that point, the network operator accepts the upgraded biogas (biomethane) and is responsible that the gas fed into the network conforms to the required quality, feed-in pressure and volume of the gas network. As a general rule, an injection facility consists of the following components and sub-systems, derived from DVGW VP 265 (DVGW, 2008c).

- Compression of the biomethane to the target pressure in the gas network, or gas pressure regulation (expansion) when fed into a low-pressure distribution grid.
- Process control – measuring, monitoring and regulation of all parts and parameters of the facility.
- Monitoring the safety of the feed-in station by means of instruments and mechanical guards (filters, safety shut-off valves, gas backflow guard, gas pressure regulator, automatic shut-off valves with gas backflow to the biogas treatment facility, gas mixer, flow regulation), including protection of the upstream and downstream equipment in terms of pressure, temperature and composition of the gas.
- Measuring the gas characteristics, including monitoring the heating value/Wobbe index of the biomethane and calibrated heating value measurement. (The Wobbe index is an indicator of the interchangeability of fuel gases and is named after Goffredo Wobbe. The Wobbe



HV, heating value; AN, contractor / GU prime contractor; AG, client or customer; BGAA, biogas upgrading facility, which is for example within the property of client; EHA, power grid operator (DSO)

16.1 Schematic layout of a standard biogas feed-in facility (source: Oliczewski, 2011).

index is the ratio between heating value of the fuel gas and its specific gravity.)

- Calibrated volume metering with volume conversion calculation to standard conditions.
- Gas conditioning facility for obtaining the required combustion characteristics by the addition of liquefied petroleum gas (LPG; see glossary, Section 16.10) and/or air if the gas quality cannot be obtained by another method.
- Provision of data relevant to the network operator (remote monitoring, data transfer).
- Network connection pipeline for feeding the treated biogas into the natural gas network.

Odorization of the biogas is an additional process. It is carried out according to DVGW G 260 (DVGW, 2008a) and G 280 (DVGW, 2008d) and is necessary if the biogas is fed into an end distribution network. Capacity bottlenecks can occur in end distribution networks and require feeding the gas back into an upstream network section of higher pressure. Sometimes, when gas is transferred into a sensitive section of the network, the gas must be deodorized. This can be avoided by controlled odorization of the biogas using a demand-driven odorization facility.

Generally, biogas feed-in stations differ mainly in the quality of the components, the redundant design of some or all components and the local conditions (grid pressure, gas quality, distance of the biogas facility to the gas network), the type of gas compression and conditioning. The main units and components of a biogas feed-in facility are now described.

16.3.2 Gas compression

The design of the compressor depends on the grid pressure of the natural gas grid (delivery pressure) and the gas upgrading system (inlet pressure). The higher the pressure difference the more power is necessary. The work the compressor must perform and therefore the cost of compression increases by the power of two of the pressure difference. When selecting a suitable compressor for a feed-in station, it should be noted that oil-lubricated compressors may contaminate the biogas. According to DVGW G 260 (DVGW, 2008a), the biomethane must be technically free of oil vapor and dust. Oil-free compressors are thus preferred; although they are free of contaminants, more methane might be lost and equipment wear is distinctly higher. In many facilities, lost gas is returned to the biogas treatment facility. The efficiency of a dry running compressor is also lower. Furthermore, it should be noted that the compression of steam-saturated gas produces water, which must be removed.

If higher pressure differentials are required, the compressor needs to be cooled. Depending on the end pressure, flow rate and initial pressure, one-stage or two-stage compressors can be used. Critical parameters for the selection of a compressor are volume flow and pressure after compression (network pressure). Because only low volume flows are involved, screw or piston compressors are most often used. Screw compressors require less maintenance and are less susceptible to technical trouble than piston compressors, but they have distinctly higher capital expenditure and operating costs. The higher purchase price and operating costs of a screw compressor must be weighed carefully against the benefit of higher availability.

If the biogas is fed into a high-pressure transport network, two-stage compression is usually necessary. In this case, a screw compressor can serve as the first compression stage and the second stage is provided by a piston compressor.

16.3.3 Pressure regulating and metering devices

Pressure metering and regulating devices are included in the technical equipment for pressure regulation and gas volume metering. Gas pressure regulating facilities regulate and limit the fluctuating inlet pressure and expand the gas to a uniform, lower delivery pressure. Usually, gas pressure regulating facilities are only needed when biomethane is fed into a low-pressure natural gas grid. Gas meters register the gas flow in the operating state. Together with pressure and temperature probes and determination of gas composition, the gas volume can be converted to a standard state according to calibration standards (Nm^3 or m^3 STP). Depending on the required safety, accuracy and cost effectiveness, displacement meters or flow meters are used.

16.3.4 Determination of gas composition

Constant monitoring of the gas composition, particularly the combustion characteristics of the treated biogas, is important for complying with the requirements on gas quality (as stated in DVGW G 260 and DVGW G 262) and the custody transfer metering for accounting purposes according to DVGW G 685 (DVGW, 2008e). Readings of the gas composition (CH_4 , CO_2 , O_2 , N_2 , H_2 and other trace substances) allow defining combustion characteristics such as superior heating value, inferior heating value, Wobbe index and standard density (see glossary in Section 16.10). Water and hydrocarbon dew points can also be determined according to DVGW G 488 (DVGW, 1999).

Continuous monitoring of gas composition ensures that the quality of the

biomethane is maintained and, if the biomethane is conditioned with LPG or a mixture of air, the conditioning facility is also monitored. Generally, two measuring methods have become standard: process gas chromatography and combustion calorimetry.

Process gas chromatographs can determine the composition of the treated biogas or the conditioned biomethane in a discontinuous mode, and can also calculate the heating value and the standard density of the gas. A chromatograph can serve several measuring points. In most cases, separate (paramagnetic or electrochemical) detection of oxygen and hydrogen is required for monitoring the limits of these substances because their allowed concentration is low (e.g. in Germany 1% (vol.) oxygen and 0.2% (vol.) hydrogen). Process gas chromatographs are not sensitive enough for these low concentrations. One drawback, particularly when several measuring points must be served, is that gas analyses can only be performed discontinuously at intervals of 3 to 6 minutes.

To determine the heating value using a combustion calorimeter, a defined gas volume is combusted completely. The heat released by the combustion provides a measure of the heating value of the gas measured. Gas composition cannot be determined using a calorimeter. Exact control of the conditioning facility (admixture of LPG) is often ensured by nondispersive infrared sensors (NDIRs), which are low-cost and supply continuous measuring signals for CH_4 or CO_2 . Minor constituents of the gas, such as H_2S , hydrogen or ammonia, can be measured by electrochemical sensors or by gas sampling and subsequent offline analysis.

In addition to gas chromatography, the density of the gas can also be determined by buoyancy or pressure swing adsorption methods; CO_2 may be determined using NDIRs. The dew point of water is determined by hygroscopic, optical or physical methods. Other parameters, such as the Wobbe index, need to be calculated.

16.3.5 Conditioning facility

Adjusting the heating value of the biogas to H-gas quality (H-gas is gas with a high heating value) with LPG is currently the standard method. On the other hand, if the biogas is fed into an L-gas network (L-gas is gas with a low heating value) air must be added to reduce the heating value. LPG conditioning facilities consist of a mixer (feeder), metering and regulating equipment and LPG storage tank. Air conditioning facilities need a gas mixer, an air compressor and suitable metering and regulating equipment. The method of CO_2 separation is critical to the amount of LPG that must be admixed and therefore to the design of the conditioning facility. If CO_2 is separated efficiently, the cost of conditioning gas with LPG is low and therefore of economic benefit. Generally, close cooperation between the

biogas producer (for minimizing the cost of gas treatment) and the network operator (for minimizing the LPG cost) is necessary. As a general rule, the cost of LPG conditioning is substantially higher than the cost of a higher degree of CO₂ separation.

16.3.6 Gas mixing facility

If biomethane is fed at low ratios into the natural gas network, conditioning may be not required. In that case, the gas enters a gas mixing facility (mixer) in which the treated biomethane is mixed thoroughly with the natural gas of the network (base gas).

16.4 Biomethane quality adjustments

According to DVGW G 260 (DVGW, 2008a) and DVGW G 262 (DVGW, 2008b), injection of biogas is possible either as a complementary gas or as an additional gas. A complementary gas is a gas whose combustion behaviour is similar to that of the local distributed natural gas in the distribution network (base gas) but whose composition may differ slightly.

An additional gas has distinctly different combustion characteristics and gas composition to those of the natural gas and can only be admixed to a limited extent. The permitted rates of admixture are restricted because DVGW G 262 requires that additional gases can be mixed with natural gas when 'the requirements of the public gas supply in the network downstream of the mixing point are met in terms of gas use and settlement', i.e. when the gas composition and the heating value does not change considerably.

Regulation G 685 (DVGW, 2008e) states that the maximum permitted deviation of the heating value at the consumer level must be less than 2% as compared with the settlement heating value. This means that the permitted rate of admixture of biogas depends on the volume flow of the natural gas and the combustion characteristics of the biogas injected. The higher the base gas flow, the higher the permitted amount of additional gas and, the greater the deviation of the composition and the combustion characteristics of the additional gas from the base gas, the lower the permitted rate of admixture.

With reference to the provisions of the DVGW regulations, the following network compatibility measures can be applied:

- heating value adjustment by LPG
- computer-based heating value reconstruction method
- network zoning into districts with fixed heating value
- feed-in as additional gas/complementary gas.

These measures should ensure that biomethane fed into the gas network and

the correct settlement, according to DVGW G 685, meet all the requirements of calibration regulations at the customer's end.

16.4.1 Heating value adjustment by LPG

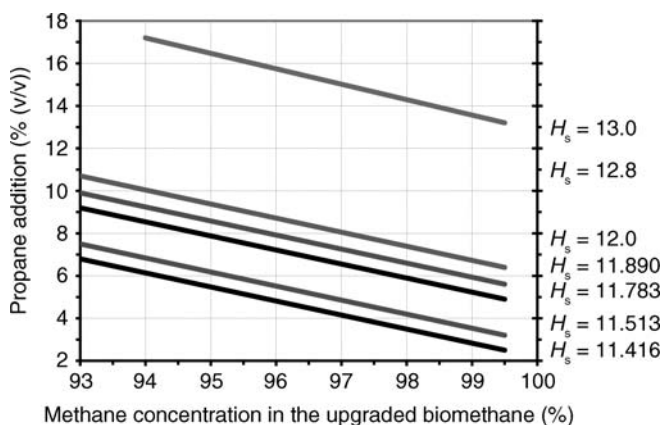
Where biogas is fed into the public gas supply network, heating value adjustment by LPG is the standard method of achieving the network compatibility required by DVGW G 685. The addition of LPG mainly raises the heating value of the treated biogas to the heating value of the natural gas distributed in the local network. In some cases, LPG and air must be added systematically to adjust the network compatibility of the biogas because not only is the heating value (in terms of the superior heating value at standard temperature and pressure (STP)) important, but so are the Wobbe index (STP) and the relative density (methane number) of the gas. The Wobbe index is the quotient of the heating value and the square root of the relative density (quotient of gas density and density of dry air at equal temperature and pressure).

Conditioning commonly uses LPG composition of 95% propane and 5% butane according to DIN 51622 (DIN, 1985). DIN 51622 defines different classifications for LPG and specifies the permitted limits for sulfur and other trace elements as well as the permitted fractions of alkenes (butene, propene and their isomers). It is also possible to use other LPG compositions and thereby keep within the limits set out in DVGW G 486 (DVGW, 1992) for propane and butane concentrations with appropriately mixed LPG. Generally, LPG mixtures with a butane content of up to 60% are permitted. This may be considered for some individual cases (e.g. when feeding biogas into a natural gas network with high heating values) because LPG cannot be added in any quantity.

Apart from heating value, the following restrictions also need to be observed.

- For application in engines, the methane number (MN) is important. It is defined by the composition of methane and hydrogen: 100% methane corresponds to $MN = 100$. The MN defines the knocking stability; $MN = 70$ is considered to be the lower limit for vehicle fuel.
- The danger of condensation of higher hydrocarbons, for example due to compression or expansion at natural gas filling or transfer stations, needs to be considered.

Figure 16.2 illustrates the required LPG concentrations for obtaining typical heating values within the gas network downstream of the mixing point as a function of the upgrading level of biomethane. The following different heating values were assumed for the German gas grid:



16.2 Gas mixture examples with their heating values H_s in kWh/m³ as a function of the biogas upgrading level and propane addition (source: Urban, 2010)

- fluctuation margin of H-gas, southern region of Germany (11.416–11.513 kWh/m³)
- fluctuation margin of H-gas, North Sea region of Germany (11.783–11.89 kWh/m³)
- gas with a heating value of 12 kWh/m³ (in the figure)
- maximum upper heating value of H-gas, north Germany (12.8 kWh/m³)
- upper heating value limit of H-gas (13.0 kWh/m³).

In addition to the DVGW set of codes and DIN standards for LPG, other regulations such DIN 51624 Automotive fuels (DIN, 2008) define standards for the permitted admixture of LPG to natural gas. In the case of a natural gas filling station, the permitted molar fraction of propane/butane in the total mixture may be limited to 6 and 2 mole % respectively. DIN 51624 also requires a methane number higher than 70.

Technically, conditioning gases can also be admixed before the biomethane is compressed to the required feed-in level. High operating pressure has no effect on the technical concept of the conditioning facility. Independent of the network pressure, the limiting factors for conditioning are only the highest possible mole fractions of the gases for conditioning the gas mixture.

Considering the gas grades distributed in Germany (Table 16.2) it should be noted that the injection of biomethane fulfilling all legal requirements is physically not possible if the natural gas has a heating value higher than 12.0 kWh/m³ (43.2 MJ/m_n³) when LPG is used for conditioning.

Injection of biomethane into pipelines with highcalorific value natural gases can only be achieved under one of the following conditions.

Table 16.2 Typical combustion data of natural gases distributed in Germany, H-gas grade

H-gas	North Sea/Dornum	Dong gas (DK)	RWE South	Waidhaus (CIS)	Philips Emden	Hünxe
Density	0.8086	0.8099	0.8202	0.7464	0.8300	0.8103
Relative density, d	0.6254	0.6264	0.6344	0.5773	0.6419	0.6267
Superior heating value H_{sr} , STP (kWh/m ³)	11.492	12.076	11.337	11.226	12.028	11.551
Inferior heating value H_{ir} , STP (kWh/m ³)	10.381	10.919	10.244	10.126	10.878	10.437
Superior Wobbe index, W_{sr} , STP (kWh/m ³)	14.531	15.258	14.234	14.775	15.013	14.591

Source: Senner *et al.* (2011).

Table 16.3 The main advantages and disadvantages of LPG addition to biomethane to achieve pipeline quality requirements in Germany

Advantages	Disadvantages
<ul style="list-style-type: none"> • Method is relatively easy to apply • Can be applied on all network levels without requiring different equipment 	<ul style="list-style-type: none"> • Very high operating costs due to high LPG input • As the addition of LPG is limited, gas compatibility cannot be obtained with some gas grades (North Sea gases I and II)

- The computer-based heating value reconstruction method is applied.
- Network zoning into districts with fixed heating value is defined.
- Biogas is fed-in as additional gas.

Fuel gas conditioning with LPG, even if practised by many gas network operators, entails very high operating costs. Therefore, the feasibility of the other network compatibility measures should also be considered. Table 16.3 summarises the main advantages and disadvantages for LPG additions to biomethane in the context of Germany.

16.4.2 Computer-based heating value reconstruction method

The heating value can subsequently be determined for any discharge point from a network with a computer-based heating value reconstruction method or heating value tracking system (REKO system). This method helps to avoid high investment costs in measurement equipment at the feeding and transfer points and high conditioning costs at biogas feeding points.

The computer-based heating value reconstruction system is a mathematical model that creates a dynamic image of a complete network or network

section (pipes, valves, feeding and withdrawal points, etc.) and can reproduce the flows, flow velocities, different gas qualities and gas mixtures on the basis of defined measuring points (pressure, gas quality and volume) at any point within the network. Based on the calculated flow velocities and the gas quality determined at fixed points, the quantities involved in mixing processes at the point of confluence can be calculated and the quality and quantity of all mixing situations can be identified. However, the reconstruction of the combustion characteristics at any point in the system can only be correct if all aspects of the following parameters are measured.

- All volumes fed in or discharged.
- Pressures for the monitoring system.
- All gas compositions at the feed-in points.
- All valve positions and operation modes of reducers and compressors.

Furthermore, exact knowledge of the pipeline system (pipeline lengths, soils, diameters, inner surface roughness, etc.) is required.

This method is often applied in connection with supra-regional transmission pipelines and regional distribution gas supply networks with few feed-in and withdrawal points. In low-pressure distribution networks the method is difficult to apply because back-mixing in interconnected networks, flow reversals or stagnant gas quantities (no flow due to lack of gas withdrawal) cannot be described mathematically. Despite that, the method was applied successfully to the Lüchow distribution network in the Wendland area in 2011. The companies E.on Ruhrgas and E.on Avacon (local network operator) created a mathematical image of an end distribution network with a total of four feed-in points (among these was one biomethane feed-in point) in a computer-based heating value reconstruction model. They performed constantly recurring gas analyses at defined points within the network and referenced the analytical results to the results calculated by the computer-based method. The accuracies required under calibration legislation were met without exception. In light of this, E.on Ruhrgas filed an application for registration of this method by the Physikalisch Technische Bundesanstalt (PTB). (The PTB based in Braunschweig, is the German federal authority responsible for legal metrology under the auspices of the Federal Ministry of Economics and Technology and the Germany National Metrology Institute providing scientific and technical services.) The main advantages and disadvantages of the computer-based heating value reconstruction method are summarized in Table 16.4.

Accuracy of the heating value measurements of 0.8% of the specified restricted measuring range required by calibration legislation can be maintained by such systems. This was proven by several system installations inspected and tested by the PTB (Office of Weights and Measures).

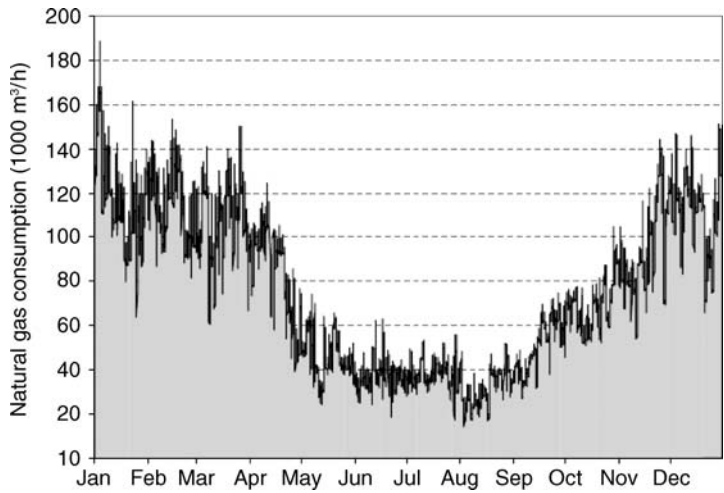
Table 16.4 Main advantages and disadvantages of the computer-based heating value reconstruction method

Advantages	Disadvantages
<ul style="list-style-type: none"> • Little or no admixture of LPG • Comparatively low operating costs 	<ul style="list-style-type: none"> • High initial cost • The impact of a larger number of feed-in points on the function of REKO systems is not yet known • Often not practicable in end distribution networks due to high level of interconnection or stagnant gas flows

16.4.3 Network zoning into districts with fixed heating value

In current practice, several distinct local networks are taken together to form a district network with a fixed settlement heating value. The closed network thereby created can be defined by discrete feed-in and discharge points. For example, district networks predominantly fed with biomethane can be set up on the local distribution network level. In this case, the feed-in point of the biomethane facility would automatically be the main supply of the network in question. As such, the heating value of the gas for end consumers can be calculated essentially by the feed-in heating value of the biomethane facility according to the rules set out in DVGW G 685 (DVGW, 2008e), and conditioning the biomethane with LPG is not required. A precondition for this is that the biomethane meets the requirements of DVGW G 260 (DVGW, 2008a). However, this model is of limited value due to the high-load flow fluctuations in these distribution networks during summer and winter. An example of fluctuating demand in a local grid is shown over the period of one year in Fig.16.3.

The setting up of separate gas distribution districts with fixed heating value should be considered very carefully because the dimensions of the network, in combination with the output of the biogas facility, may require that either biomethane is fed into the next higher pipeline level (which requires conditioning the biomethane during the warm season and/or natural gas has to be added during the peak season). In the latter case, either the biomethane would have to be conditioned with LPG or the natural gas with air to ensure that the maximum permitted deviation of 2% of the feed-in heating value of several points feeding into the common network in DVGW G 685 is not exceeded. Either way, there are advantages and disadvantages (Table 16.5).



16.3 Seasonal variation of the natural gas supply within the network of E.on Avacon AG (source: Urban, 2010).

Table 16.5 Main advantages and disadvantages of separate local distribution grids

Advantages	Disadvantages
<ul style="list-style-type: none">• Can be applied at little cost in suitable partial network sections• Comparatively low operating costs	<ul style="list-style-type: none">• Application in end distribution networks only possible after case-to-case examination• Not practicable in transportation networks; practicable with restrictions in regional distribution networks

16.4.4 Biomethane feed-in as additional gas

Additional gases are gas mixtures whose composition and combustion characteristics are substantially different from those of the grid gas. Additional gases can be added only to a limited extent. The rate at which additional gas can be added is governed by the combustion characteristics of the mixture downstream of the mixing point.

The definition of combustion behaviour occurs only after mixing of biomethane with the natural gas flow. The higher the volume flow of the base gas in comparison with the volume flow of the biomethane, the wider the heating value of the biomethane can deviate from the heating value of the base gas. The maximum permitted deviation from the heating value used in the settlement in the respective network section is, again, 2%.

Feeding biomethane as additional gas in supra-regional transmission

Table 16.6 Main advantages and disadvantages of injecting biomethane as an additional gas

Advantages	Disadvantages
<ul style="list-style-type: none"> • Little or no admixture of LPG • Very cost-effective 	<ul style="list-style-type: none"> • Applicable only in network sections with high base gas flows throughout the year (selected sections on the transport network level) • Individual application in optimal sections; redundant conditioning to be provided

pipes is an interesting method because of the high transport capacities available. The investment and operating costs of biomethane injected as additional gas when compared with the other methods already discussed look very promising unless the volumes are very large and thus require extended and expensive mixing lines. The very low operating costs and the simple construction of the network connection are advantages that may result in lower overall costs.

Possible flow reversals in the feed-in pipeline may be critical to the applicability of this method. Generally, high flexibility of operations management is necessary on the transport level to avoid supply bottlenecks. This can give rise to pendulum zones or changes of the flow direction in some cases, or in certain network sections. Flow reversal in a pipeline feeding additional gas can cause a fluctuation of the heating value of more than 2%. The mixing line in such network sections should be equipped with sample loops at both ends. In addition, if load flow reversal occurs and biomethane can be added at several points, the continuous feeding of biomethane as an additional gas cannot be ensured without a redundant fuel gas conditioning facility. Alternatively, injection of additional gas is not required at times when a reversal of the flow direction in the respective network section is likely. Conditioning with LPG is certainly the redundant technical solution of choice for meeting the requirements of calibration regulations.

In summary, injection of biomethane as additional gas can be a very cost-effective measure when high natural gas flows are involved. The advantages and disadvantages of this approach are summarized in Table 16.6.

16.4.5 Comparison of the different network compatibility measures

Heating value adjustment by addition of LPG can be achieved at virtually all gas network pressure levels provided the heating value of the natural gas flow is not higher than 12.0 kWh/Nm³ (Table 16.7) As a consequence, this

Table 16.7 Comparison of the network compatibility measures

	End distribution network	Regional network	Long-distance transport network
LPG conditioning	<ul style="list-style-type: none"> • State-of-the-art • No particular requirements on the network • Not possible in supply areas with a heating value above 12.0 kWh/m³ • High operating costs 	<ul style="list-style-type: none"> • State-of-the-art • No particular requirements on the network • Not possible in supply areas with a heating value above 12.0 kWh/m³ • High operating costs 	<ul style="list-style-type: none"> • State-of-the-art • No particular requirements on the network • Not possible in supply areas with a heating value above 12.0 kWh/m³ • High operating costs
Computer-based heating value reconstruction method	<ul style="list-style-type: none"> • Technically feasible • Less economic viability than in a regional network 	<ul style="list-style-type: none"> • Technically feasible • Less economic viability than in a long-distance transport network 	<ul style="list-style-type: none"> • Good to implement despite high capital and administrative costs
Network zoning into districts with fixed heating value	<ul style="list-style-type: none"> • Closed-loop network with clearly defined feed-in and discharge • As a rule, requires only little capital expenditure 	<ul style="list-style-type: none"> • Possible with limitations 	<ul style="list-style-type: none"> • Practically impossible
Biogas feed-in as additional gas	<ul style="list-style-type: none"> • Not possible, as a rule 	<ul style="list-style-type: none"> • Possible with limitations 	<ul style="list-style-type: none"> • Technically easy due to high base gas flow • Little expenditure

makes LPG conditioning the present state-of-the-art. Widespread implementation of a REKO system for simplification of biogas feed-in is unlikely considering the high initial capital cost due to the high demand for measuring and metering equipment. However, many transport pipelines with limited feed-in points for biomethane and some regional distribution gas supply networks already apply a computer-based heating value reconstruction method.

In some cases, network zoning into districts with fixed heating value is a valuable solution if biomethane is injected in large quantities and provides the base load of gas consumption. Network zoning into districts at supply transport network level is not to be expected.

When compared with gas conditioning using LPG, there are several alternative methods to ensure the network-compatible feed-in of biomethane that are independent of the network level and the network

structure. On a transport grid level, the application of a computer-based heating value reconstruction method is the most widely practised alternative to conditioning; in some cases, feed-in as additional gas is also possible. In a regional network and, particularly, in the end distribution network, the definition of heating value zones should be envisaged. In the long term, computer-based heating value reconstruction methods could become equally cost effective.

16.5 Economic aspects of biomethane injection

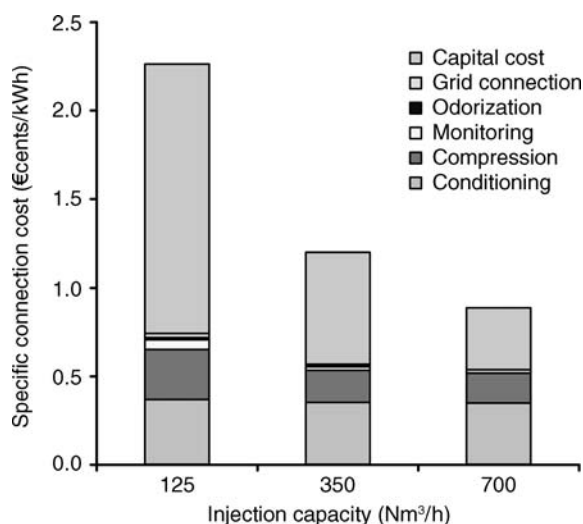
The total costs of network connection (investment and operating costs) vary greatly. The most important factors are volume flow, network pressure and distance to the gas network (also see Table 16.2). The investment costs are further governed by the quality of design (redundancy) and the operating costs due to the nature of the energy value adjustment (LPG admixture or alternative method).

The highest investment costs are due to the compressor assembly (approximately 60% of the investment), followed by the measuring equipment (metering and gas quality measurement) and pipeline construction costs (connecting pipeline). The operating costs, on the other hand, are dominated by the costs of the conditioning gas and electricity consumption for recompression to network pressure. Absolute investment costs hardly increase with the size of the facility, which explains why small installations entail relatively high specific costs (Fig. 16.4). A project requiring a long pipeline should be equipped with a redundant compressor unit. In that case, the investment costs will double.

As an example, the specific investment costs for connection to a medium-pressure network (maximum network operating pressure of 16 bar) drop from 12,240 €/m³ gas throughput per hour (for a facility with 125 m³/h biomethane) to 2457 €/m³ hourly gas throughput (700 m³/h biomethane). The picture is similar for the operating costs (full cost calculation), which are dominated by the capital costs even for facilities with medium gas throughputs (up to 350 m³/h biomethane). Injection into a distribution grid with a pressure <1 bar involves low investment and operating costs. When biogas is fed into high-pressure pipelines (e.g. 55 bar), compression costs will go up by up to 50% when the network pressure is raised from 16 bar, but will still account for only one third of the annual operating costs. Table 16.8 shows examples of costs for gas network connections.

16.6 Optimization and efficiency increase

Many mature upgrading technologies for the separation of CO₂ are commercially available (see Chapter 15 of this book). Leading suppliers of



16.4 Specific network connection costs in cents€/kWh as a function of feed-in capacity in Nm³/h (source: Urban, 2010).

treatment equipment increasingly offer all-in-one systems including desulfurization, upgrading, off-gas treatment, drying, feed-in station, heat recovery system for heating the digester, etc. Because most treatment methods are well engineered, no dramatic cost reductions should be expected in the foreseeable future. The trend is towards optimized coupling of the different steps, high industrial quality, automation and increased energy efficiency. The primary target is to reduce costs, electricity consumption and greenhouse gas emissions (methane losses), and develop synergies between the biogas plant, upgrading and injection. All leading suppliers offer off-gas treatment facilities for reducing methane emission and heat recovery systems for heating the digester.

The debate over optimization and energy efficiency potential associated with gas network connection is substantially influenced by controversial discussions among the suppliers of gas and gas network operators. These include, for example, the intensive debate and assessment of the availability of the feed-in facilities (redundancy), the minimum quality requirements (minimum methane content vs. cost of gas conditioning) and the economically reasonable size of a facility (limitation of investment and expansion costs).

Optimization of investment costs and plant availability (minimization of lost profit) strongly depends on the volume of biomethane produced and the pressure level. Substantial cost reductions (both investment and operating costs) can be obtained by eliminating compressor redundancy. This is particularly meaningful, where small biomethane volumes are fed into end distribution networks. However, this would be at the expense of lower

Table 16.8 Overview of typical investment costs of network connection stations as a function of feed-in capacity

Network level: Regional transport network, PN 16			
Maximum operating pressure (MOP)	Upstream pressure 800 mbar; MOP 10–16 bar		
Base gas heating value	11.3 kWh/Nm ³		
Network connection	500 m crossing mostly open space, open by drilling		
Feed-in facility concept	Single-lane design, network compatibility (DVGW G 685) ensured by heating value adjustment with LPG, 90% availability of feed-in station and network connection, no redundant compressor		
Feed-in capacity	125 m ³ STP/h	350 m ³ STP/h	700 m ³ STP/h
Individual item costs			
Pipelines, incl. civil eng. work, connection (€)	200 000	200 000	200 000
Conditioning w/o LPG tank (€)	100 000	100 000	100 000
Measurement/metering (€)	260 000	280 000	300 000
Odorization (€)	30 000	30 000	30 000
Compression (€)	300 000	350 000	400 000
Gas station building (€)	100 000	150 000	150 000
Gas pressure regulation/control equipment (€)	80 000	80 000	80 000
Electrical and remote control equipment (€)	340 000	340 000	340 000
Design approval documentation (€)	120 000	120 000	120 000
Total capital expenditure (CAPEX) (€)	1 530 000	1 650 000	1 720 000
Spec. CAPEX (€/m ³ STP h ⁻¹) (€)	12 240	4714	2457
Annual CAPEX ^a (€)	157 300	169 700	176 900
Spec. annual CAPEX (cents/kWh H _s) ^b	1.46	0.56	0.29
Operational expenditure (OPEX)			
Auxiliary. power consumption (€)	36 000	36 000	36 000
HV adjustment with LPG (€)	45 000	99 000	182 000
Odorization (€)	1200	1400	1600
Compression costs (power) (€)	20 300	35 100	54 800
Total OPEX (€)	102 500	171 500	274 400
Spec. OPEX (cents/kWh H _s) ^b	0.87	0.52	0.42

^a Annual allocation depreciation and redemption, 15 years' depreciation, 6% annuity rate.

^b Reference: 8000 operating hours per year, H_s (STP) biomethane 10.74 kWh/m³ STP. Source: Urban (2010).

equipment availability. Results of cost calculations show that for high feed-in volumes ($700\text{ m}^3/\text{h}$ biomethane), high equipment availability is a must and therefore all major units (e.g. the compressor) should be redundant. Equipment availability cannot only be improved by redundant equipment but also by preventive maintenance and repair and shorter maintenance intervals.

Under a macroeconomic perspective, investment in the network connection is less important than the running costs and therefore particular attention should be given to the choice of the grid connection point and the method of gas conditioning.

Lopsided optimization of feed-in facilities should be avoided. Savings in investment costs by the gas supplier should not be made at the expense of the gas network operator. There is no single solution available because in practice many fringe conditions must be considered.

There is a chance that more cost-effective monitoring equipment may become available in the near future, but associated potential cost reductions cannot be calculated at this point in time. The possibility of cost reductions from the manufacture of standardized components in large numbers is far better and therefore good engineering practice and simple, appropriate technical standards should be the priority targets.

The gas treatment technologies available in the market are mature and as such do not allow for major cost reductions. Improved maintenance and repair strategies and further optimization of energy efficiency might be overcompensated by stricter safety and emission control standards. It is thus more likely that the combined cost of biomethane production and feed-in will remain at the present level. Recompression still has technical optimization potential because the operating expenditure for recompression accounts for about 60% of total operating costs. Furthermore, the methane loss should be reduced to a minimum (lost profit) and product gas lost from compression be returned to the process.

16.7 Conclusion and future trends

In the first decade of the 21st century in Europe there has been a growing trend towards upgrading of biogas to pipeline-quality biomethane for feed-in into natural gas networks. Different countries have approached grid injection of biomethane in different ways until quite recently. Adoption of the European renewables directive in 2009 (European Commission, 2009) formalized the approach to grid injection of biomethane, at least in Europe. The technical requirements for grid injection set by the European renewables directive have provided an impetus to provide more uniform rules for implementation. At the same time, the rapid expansion of biomethane production has demanded the establishment of comprehensive rules for grid

connections. As a consequence, legal frameworks have been set up in Europe. One of the most developed examples has been described in detail in this chapter – the Gas Network Access Ordinance (GasNZV) in Germany. This is often considered the ‘Highway Code’ for biomethane. The Renewable Energy Sources Act has become the driving force for capacity building of biomethane production and grid feed-in in Germany.

Similar legal frameworks are being implemented in other countries as biomethane production and use continue to grow rapidly. Biomethane is a flexible fuel that can be used wherever natural gas is used without any need to change settings on equipment designed to use natural gas. In regions where a natural gas grid already exists, there is a ready-made system for biomethane distribution with minimal needs for new investments beyond making grid connections.

The main challenge facing biomethane grid injection is cost. Also, in the future, there will be a growing need to balance gas supply and demand, particularly in low-pressure parts of the network and at times of low demand such as in the summer months. Managing the whole natural gas/biomethane grid with very many injection points will become a greater challenge as the amount of biomethane injected increases. At the same time, there is a strong potential benefit to be harnessed – using the storage capacity of the gas grid to allow compensation for fluctuations in power production from renewable energy sources such as wind and solar.

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16.10 Appendix: glossary

Additional gas: (also referred to as supplementary gas) a gas with distinctly different combustion characteristics and composition to those of the local distributed natural gas (base gas) and that can only be admixed to a limited extent with the base gas.

Base gas: local distributed natural gas with distinctive combustion behaviour and gas composition which sets default values for any gas feed-in.

Complementary gas: a gas whose combustion behaviour is the same as that of the natural gas in the distribution network (base gas) but whose composition and basic combustion characteristics are different.

Heating value (H): the heating value or energy value of a substance, e.g. a fuel, is the amount of heat released during the combustion of a specified amount of it. The heating value is a characteristic for each substance. It is measured in units of energy per unit of the substance, usually mass, such as: kJ/kg, kJ/mol. Within the gas industry the heating value is usually related to m^3 STP.

Inferior heating value (H_i): also known as lower heating value (LHV) (net calorific value (NCV) or lower calorific value (LCV)) and is determined by subtracting the heat of vaporization of the water vapor from the higher heating value. H_i assumes that the latent heat of vaporization of water in the fuel and the reaction products is not recovered.

Liquefied petroleum gas (LPG): flammable mixture of hydrocarbon gases; consists mainly of propane and butane and their isomers. Under atmospheric conditions, LPG is gaseous, distinctly heavier than air and can be liquefied at low pressure.

Relative density (d): quotient of the density of a distinctive gas (e.g. natural gas) and density of dry air at equal temperature and pressure.

Superior heating value (H_s): also known as higher heating value (HHV) (or gross energy or upper heating value or gross calorific value (GCV) or higher calorific value (HCV)), it is determined by bringing all the products of combustion back to the original pre-combustion temperature and, in particular, condensing any vapor produced.

Wobbe index (W_i): the quotient of the heating value and the square root of the relative density. Depending on the underlying heating value, there is a superior or inferior Wobbe index.

Generation of heat and power from biogas for stationary applications: boilers, gas engines and turbines, combined heat and power (CHP) plants and fuel cells

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Abstract: Biogas is produced during the anaerobic degradation of organic material. The produced biogas can be used for heat, electricity or cogeneration of heat and electricity in a combined heat and power plant (CHP). This chapter first discusses the key issues related to combustion of biogas/biomethane in different stationary equipments. It then describes the utilisation of biogas for the generation of electric power and heat in different stationary applications such as boilers, gas engines (CHP), micro turbines and fuel cells.

Key words: biogas, combustion, engines, power, stationary applications.

17.1 Introduction

Biogas is produced during the anaerobic degradation of organic material in natural and man-made environments, namely dedicated anaerobic digestion (AD) plants, sewage treatment plants and landfills. Biogas consists mainly of 55–65% methane (CH_4) and 35–45% carbon dioxide (CO_2) with trace amounts of other gases. The gas is usually saturated with water (H_2O) and, depending on the feedstock used, biogas may also contain hydrogen sulphide (H_2S), ammonia (NH_3), siloxanes and some oxygen (O_2) and nitrogen (N_2).

Biogas is considered as a CO_2 -neutral biofuel and can be used as fuel in all stationary applications suitable for natural gas. The calorific value of biogas ranges between 19.7 and 23.3 MJ/m^3 and is dependent on the amount of

CH₄ (55–65%) in biogas (Rasi *et al.*, 2007; Petersson and Wellinger, 2009). This calorific value is typically between 50 and 70% of the commercial quality natural gas calorific value of 31.6–39 MJ/m³, which depends on source and composition (Petersson and Wellinger, 2009).

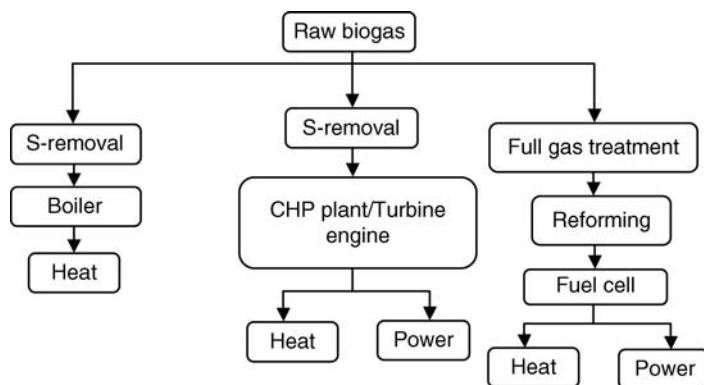
Biogas has numerous end-use applications compared with other renewable energy resources. Traditionally, biogas has been used as fuel for boilers to produce heat or for cogeneration of heat and electrical power in combined heat and power (CHP) generation plants. In CHP plants, electricity is generated by burning fuel (natural gas or biogas) and then a heat recovery unit is used to capture heat from the combustion system's exhaust stream. This heat can be converted into useful thermal energy, usually in the form of steam or hot water. These CHP systems are normally provided with a four-stroke engine or a diesel engine. Biogas can also be used in a boiler to produce steam for driving engines or turbines; examples include the organic rankine cycle (ORC), the Cheng cycle, the steam turbine, the steam piston engine and/or the steam screw engine. Other alternatives that can use biogas as fuel are Stirling engines or gas turbines, micro gas turbines, high- and low-temperature fuel cells and a combination of a high-temperature fuel cell with a gas turbine. However, biogas cleaning (see Chapter 14) is a prerequisite to meet the gas quality requirements of the equipment used (Fig. 17.1). The various utilisations of biogas in stationary applications are

- the production of heat and/or steam in a boiler (the lowest value chain utilisation)
- electricity production in CHP production with waste heat recovery
- as an industrial energy source for heat, steam and/or electricity and cooling in a micro turbine
- electricity generation by direct use of methane or reforming to hydrogen in fuel cells.

17.2 Biogas and biomethane combustion issues

17.2.1 Heat and electric power generation from biogas

Biogas properties will have a significant impact on the selection of technology for conversion to heat and/or electricity. In general, the biogas composition and production rate are influenced by the type of digestion process and feedstock used. Biogas composition and energy content will also affect the choice of equipment for biogas utilisation. For instance, de-rating is noticed in boilers due to limited volumetric throughput of the fuel into the combustion system. Moreover, boilers do not need a high-quality biogas. The maintenance cost for reciprocating engines increases with increasing



17.1 Use of biogas for various stationary applications (S-removal represents removal of sulphur compounds).

H₂S concentration and H₂S removal is necessary at concentrations higher than 1000 ppmv (Chambers and Potter, 2002). In comparison to gas engines, micro turbines are more resistant to sulphur compounds and lower oxides of nitrogen, NO_x (refers to NO and NO₂) and carbon monoxide (CO) emissions. Similarly, extensive biogas cleaning is required for the use of biogas in fuel cells. Components of concern from an emissions and equipment safety and maintenance point of view are

- reduced sulphur compounds (H₂S, mercaptans (CH₃SH), dimethyl sulphide (CH₃SCH₃, DMS), carbonyl sulphide (COS) and carbon disulphide (CS₂)) due to their contribution to SO₂ emissions, safety concerns and corrosion due to formation of sulphuric acid
- compounds containing nitrogen (N₂) due to their potential to increase NO_x emissions and potential to form nitrous oxide, N₂O (a greenhouse gas)
- chlorinated compounds due to the potential to form dioxins during combustion
- siloxanes, which on combustion transform to microcrystalline silicon dioxide (SiO₂) and deposit on valves, cylinder walls and liners, causing abrasion and blockage of pistons, cylinders and valves.

17.2.2 Biogas purification

The typical biogas composition from digesters operating in Europe is presented in Table 17.1. Depending on the source, biogas mainly contains 45–70% CH₄, 30–55% CO₂, 0–2000 ppmv H₂S and 0–590 ppmv NH₃ (Rasi *et al.*, 2007; Petersson and Wellinger, 2009). H₂S concentration is strongly influenced by the composition of feedstock used for biogas production. The

Table 17.1 Composition of biogas from dedicated AD plants, sewage treatment plants and landfill, and natural gas

Parameter	Farm-scale AD plant	Centralised AD plant	Landfill	Sewage treatment plant	Natural gas
CH ₄ (vol %)	55–60	60–70	35–65	60–65	81–89
Other hydrocarbons (vol %)	0	0	0	0	3.5–9.4
H ₂ (vol %)	0	0	0–3	0	—
CO ₂ (vol %)	35–40	30–40	25–45	35–40	0.67–1.00
N ₂ (vol %)	<1–2	2–6	<1–17	<1–2	0.28–14.00
O ₂ (vol %)	<1	0.5–1.6	<1–3	<0.05–0.70	0
H ₂ S (ppm)	25–30	0–2000	30–500	<0.5–6800	0–2.9
NH ₃ (ppm)	≈100	≈100	≈5	<1–7	0
Halogenated compounds (mg/m ³)	<0.01	<0.25	0.3–225	0–2	—
Siloxanes (mg/m ³)	<0.03–<0.2	<0.08–<0.5	<0.3–36	<1–400	—
Wobbe index	24–33	24–33	20–25	25–30	44–55
Lower heating value (MJ/Nm ³)	19.7–21.5	21.5–25.1	10.7–23.3	21.5–23.3	31–40

Note: 1 kWh/Nm³ = 3.6 MJ/Nm³.

Source: adapted with permission from Rasi *et al.* (2007); and Petersson and Wellinger (2009).

maintenance cost for reciprocating engines (four-stroke spark ignition and diesel engines) increases with increasing H₂S concentration in the biogas. H₂S scrubbing is a must if concentrations are higher than 1000 ppmv (Chambers and Potter, 2002). In addition, biogas may contain more than 500 different contaminants such as halogenated hydrocarbons, higher hydrocarbons and aromatic compounds (Rasi *et al.*, 2007). Landfill and sewage gas can also contain siloxanes, which may cause severe problems in downstream utilisation (Rasi *et al.*, 2007). Trace amounts of hydrogen (H₂), N₂, CO, saturated or halogenated carbohydrates and O₂ are occasionally present in the biogas. Usually, the mixed gas is saturated with water vapour. Depending on the biogas source and its end use, these contaminants have to be removed.

Biogas can be utilised in several ways, either as raw biogas or upgraded biomethane. The challenge with the use of biogas as a fuel is the need for gas cleaning to meet the quality requirements for the utilisation equipment. Use of untreated biogas may increase the maintenance requirements of the equipment fuelled by the biogas and can reduce its life span. As a prerequisite for effective biogas utilisation, biogas has to be cooled, drained and dried immediately after production to reduce condensation and, almost always, it has to be cleaned of H₂S.

Solid particle and foam

All biogas plants are normally equipped with filters and/or cyclones for the removal of particles in the biogas. Solid particles and oil-like components in the biogas are filtered out with the usual dust collectors, while sludge and foam components are separated in cyclones. Filters with a 2–5 micron mesh size are normally regarded as appropriate for most downstream applications (Persson *et al.*, 2006).

Hydrogen sulphide

Biogas often contains a variety of sulphur compounds, such as sulphides and disulphides. H_2S is produced from the degradation of proteins and other sulphur-containing compounds present in the feedstock. The concentration of H_2S in the biogas depends on the feedstock, and varies between 0.1 and 2% (Lastella *et al.*, 2002). H_2S is also found in landfill gas and sewage digester gases (Cox and Deshusses, 2001).

Hydrogen sulphide is toxic and strongly corrosive to many kinds of steel (Tchobanoglous *et al.*, 2003). H_2S needs to be removed, for all except the most simple burner application, in order to avoid corrosion in compressors, gas storage tanks and engines. When untreated biogas is combusted, H_2S is converted into sulphur oxides. Sulphur oxides then react with water to form sulphuric acid (H_2SO_4), which corrodes metallic components and acidifies engine oil (e.g. of the engine in the CHP unit). The reactivity of H_2S is enhanced by concentration and pressure, the presence of water and elevated temperatures. The H_2S content in biogas, at levels higher than 300–500 ppmv, damages the energy conversion process (Holm-Nielsen and Al Seadi, 2004) and also leads to catalytic converter poisoning. H_2S must be removed from the biogas or at least reduced to less than 1000 ppmv (0.1% by volume) to prevent corrosion of the boiler or to 100–500 mg/Nm³ H_2S (equal to 0.01–0.05% by volume) to prevent damage to the CHP unit and other equipment (e.g. heat exchangers and catalysts). For trouble-free operation, the residual H_2S in the treated biogas should be less than 20 mg/Nm³.

Carbon dioxide

For many applications, such as heaters, internal combustion engines or generator systems, CO_2 removal from biogas is not necessary. However, CO_2 accounts for 30–50% of the biogas volume; removal of the CO_2 thus increases the heating value of the gas, and therefore the Wobbe index, and provides consistent gas quality similar to natural gas. For use of biogas as vehicle fuel, the methane content should be more than 95%, meaning that

most of the CO_2 has to be removed. This process is normally designated as 'biogas upgrading to biomethane'. Different biogas upgrading technologies for CO_2 removal include absorption in water, physical and chemical absorption, adsorption with pressure, membrane and cryogenic processes (see Chapter 15).

Water

Biogas is normally saturated with water vapour as the AD process generally takes place at 35°C or 55°C and under wet conditions with feedstocks containing more than 70% moisture. Besides reducing the calorific value, high moisture content in biogas can cause problems as it condensates in gas pipelines, engines, etc. In addition, the condensed water can react, for example with H_2S to form ionic hydrogen and/or H_2SO_4 , which can cause severe steel corrosion. Often, the biogas has to be dried before further cleaning, by means of downstream absorption plants for example. By lowering the dew point to 5°C , biogas with a relative humidity of less than 60% at normal temperature is obtained and corrosion can be prevented (Deublein and Steinhauser, 2008).

Water vapour in biogas can be removed through suitable pipework or freeze drying to condense and remove as water. Biogas piping (minimum of 50 m length) is laid with a minimum 1% slope (10.4 mm/m) toward the collection point and the gas flow rate should not exceed $3.7 \text{ m}^3/\text{s}$ through the pipe (Vandeweyer *et al.*, 2008). The dryer is typically made of stainless steel or other corrosion-resistant material to minimise corrosion from H_2S . Corrosion from condensing acid can also be minimised by removing H_2S from the biogas prior to drying. Alternatively, water vapour can be removed by adsorption on silica gel and Al_2O_3 at low dew points or by adsorption with glycol and hygroscopic salts at elevated temperatures and by using molecular sieves.

Halogenated compounds

Halogenated compounds are substances containing one or more halogen atoms (fluorine, chlorine, bromine or iodine). Examples of such compounds in biogas are carbon tetrachloride, chlorobenzene, chloroform and trifluoromethane. These are often present in landfill gas, but rarely in biogases from the digestion of sewage sludge or organic waste. Halogens are oxidised during the combustion process. The combustion products are corrosive, especially in the presence of water, and can cause corrosion in downstream pipes and applications. They can also initiate the formation of dioxines and furans (polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans) if the combustion conditions (temperature and time) are

favourable (Allen *et al.*, 1997). The concentration of total chloride and total fluoride in biogas can range from 118 to 735 mg/m³ and 25.9 to 256 mg/m³ respectively (Allen *et al.*, 1997; Jaffrin *et al.*, 2003).

Siloxanes

Siloxanes are volatile silicones bonded by organic radicals and are generally present in landfill and sewage gas (see Dewil *et al.*, 2006). Siloxanes (C₂H₆OSi) mainly originate from silicon-containing compounds widely used in various industrial materials or consumer products such as shampoo, detergents and cosmetics. During biogas combustion, siloxanes are converted to microcrystalline silicon dioxide (SiO₂), a residue with chemical and physical properties similar to glass. These crystalline deposits have a surface thickness of several millimeters. Extensive engine erosion or blockage can occur due to the deposition of siloxanes on engine valves, cylinder walls and liners. In gas engines, siloxane deposits usually form on nozzles and blades, causing erosion of the turbine blades and subsequently lowering the operating efficiency (Tower, 2003). To prevent premature engine failure due to silicate deposition, manufacturers of gas engines introduced a limit value of 1 mg/l of silicon in the oil of gas engines (Prabucki *et al.*, 2001) or a maximum total siloxane concentration of 5 mg/Nm³ of biogas (Environment Agency, 2004). Silicate deposition can also result in poor heat transfer in heat exchangers and can cause abrasions to the blades in turbines. The silicon limit imposed in micro turbines is less than 10 ppb (Accettola *et al.*, 2008). In addition, the glassy residues inactivate the catalyst of the emission control system and thus reduce the removal efficiency of combustion products (CO and NO_x). A similar process occurs in fuel cells, resulting in a lower voltage and power density for a given current density (Accettola *et al.*, 2008).

Siloxanes can be removed from biogas by means of adsorption onto activated carbon, activated alumina or silica gel. A significant amount of siloxanes (90–95%) can be removed along with the moisture when the gas is dried, for example at –23°C (low-temperature drying system). Activated carbon or graphite media scrubbers followed by a gas dryer would offer a cost-effective means of removing siloxanes. Chilling the gas to 5°C with a gas dryer would remove some of the water and approximately 30–40 % of the siloxanes (de Hullu *et al.*, 2008). The remaining siloxanes can be removed using a scrubber system.

Ammonia

Ammonia is formed during the anaerobic degradation of feedstocks rich in protein. Ammonia concentration in biogas is generally very low, not

exceeding 0.1 mg/Nm^3 (Persson *et al.*, 2006). A high concentration of ammonia in biogas is a problem because combustion of ammonia in gas engines leads to the formation of nitrous oxide (NO_x). Most engines can accept ammonia concentrations of 100 mg/Nm^3 (Persson *et al.*, 2006). Ammonia formation can be avoided by controlling the biogas process, as ammonia is formed at high pH and temperature. Adjusting the C/N ratio of the feedstock can also avoid ammonia formation. The removal of ammonia is usually combined with other biogas cleaning procedures.

Oxygen and nitrogen

The presence of O_2 and N_2 in biogas can lower the heating value of the gas and cause corrosion in gas pipelines and other equipment. Normally, O_2 and N_2 are not present in biogas from sewage and dedicated AD plants, as methane is formed under anaerobic conditions (without O_2). On the other hand, landfill gas contains O_2 (1–3% vol) and N_2 (1–17% vol) as some air may be sucked in together with the landfill gas through the underpressure collection system (Rasi, 2009). Moreover, a high O_2 content in the biogas (6–12%) can lead to an explosion due to presence of combustible CH_4 in the biogas mixture (Vandeweyer *et al.*, 2008). Finally, the removal of O_2 and N_2 – if present in large quantities – can be costly and impede the use of biogas for vehicle fuel or grid injection. Oxygen in biogas is generally removed during the desulphurisation process. Other applicable methods include adsorption processes (e.g. with activated carbon or molecular sieves).

17.3 Utilisation of biogas for the generation of electric power and heat in stationary applications

Over the years, biogas collection and utilisation technologies have improved. Several technologies that convert biogas to more useful forms of energy are now available. For direct substitution of biogas for natural gas, the biogas has to be cleaned of impurities (especially H_2S , siloxanes, water vapour etc.) and the equipment has to be slightly modified to prevent corrosion and maintain the right gas feed pressure and fuel-to-air ratio in order to ensure flame stability.

Table 17.2 presents a comparison of typical power generation units with their capacities, efficiencies, fuel consumption and heat recovery rates. The performance and characteristics of some of these technologies have improved in recent times due to increased experience of using of biogas for electricity generation.

Table 17.2 Comparison of biogas power generation in stationary applications

Parameter	Engine	Gas turbine	Micro turbine	Stirling engine	Fuel cell
Unit capacity (kW _e) ^a	110–3000	3500–15 000	30–300	<150	300–1500
Plant size	Small to medium	Large	Small	Small	Small
Electrical efficiency (%)	30–42	25–40	25–30	30–40	40–45
Thermal efficiency (%) ^b	40–50	30–50	30–35	35–40	30–40
Overall system efficiency (%)	70–80	70–75	55–65	65–80	75–80
Power/heat ratio production control	Not possible	Very good	Very good	Very good	Good
Biogas purification requirement	Medium	Medium	Medium	Low-medium	High
Emissions NO _x	High 500–700 mg/Nm ³	Low 25–50 mg/Nm ³ flue gas	Low	Very low	Extremely low (3 mg/Nm ³ flue gas)
Alternative fuel source	Liquid gas	Natural gas	Natural gas, kerosene, fuel oil	Natural gas, oil, biomass	Natural gas
Investment costs (€/kW _e) ^c	400–1100	900–1500	600–1200	1300–1500	3000–4000
Operation and maintenance cost (€/kWh) ^d	0.01–0.02	0.005–0.010	0.008–0.015	0.003–0.005	0.003–0.010

^a Unit capacity varies depending on manufacturer.

^b Heat recovery is estimated as a percentage of fuel input.

^c Installed costs vary with type and amount of auxiliary equipment.

^d Maintenance costs are dependent on gas quality.

Source: adapted with permission from Chambers and Potter (2002), Obernberger *et al.* (2003) and Deublein and Steinhauser (2008); Wiley-VCH Verlag GmbH & Co. KGaA, Germany.

17.3.1 Biogas as fuel for boilers

The production of heat (thermal energy) in boilers is the most common and simple way of using biogas. The conversion efficiencies for heat production from biogas are typically 75–85% (Krich *et al.*, 2005). Conventional boilers that are used for natural gas can be adjusted for biogas use by changing the air-to-gas ratio and enlargement of the fuel orifice or burner jets. In addition, the combustor needs to be modified in order to handle the high flow rate of biogas, which is needed as it has lower energy content than natural gas.

Boilers can use low-quality biogas for combustion. For successful operation, the operating temperatures should be above the dew point in order to prevent condensation. To prevent corrosion from H₂S and water vapour, all metal surfaces of the housing should be coated.

17.3.2 Biogas as an engine fuel

Use of biogas as fuel for electricity generation in gas engines is a commercially available and proven technology all around the world (Chambers and Potter, 2002; Krich *et al.*, 2005; Deublein and Steinhauser, 2008; US EPA CHPP, 2008). Most of the biogas installations use spark-ignited natural gas or propane engines that have been modified to operate on biogas. Diesel and four-stroke gasoline engines have also been modified to use biogas. Waste heat from engine operations is used frequently in CHP applications.

17.3.3 Four-stroke engines

The present-day four-stroke biogas engines were originally developed for natural gas and therefore can be used for biogas with little or no engine modification. Four-stroke engines are available with capacity ranging from a few kilowatts to 10 MW with an approximate life span of 60 000 h and an electrical efficiency of 35–40% (Deublein and Steinhauser, 2008). Four-stroke engines with electrical efficiencies above 40% are generally equipped with a recuperator (US EPA CHPP, 2008). The amount of fuel energy converted to electricity generally increases with size, ranging from 30% for small units to 40% for large engines. The amount of fuel converted to thermal energy is 40–50%, resulting in overall efficiencies of 80–85% (Chambers and Potter, 2002). In general, electrical conversion efficiency decreases with an increase in the CO₂ concentration in the biogas and, consequently, increased anti-knock properties. Classification of reciprocating engine types based on available rating is presented in Table 17.3.

Both spark ignition and diesel four-stroke engines complete a power cycle

Table 17.3 Classification of reciprocating engine types based on available MW rating

Speed classification	Engine speed (rpm)	Stoichiometric /rich burn, spark ignition	Lean burn, spark ignition	Dual fuel	Diesel
High	1000–3600	0.01–1.5 MW	0.15–3.0 MW	1.0–3.5 MW	0.01–3.5 MW
Medium	275–1000	None	1.0–6.0 MW	1.0–25 MW	0.5–35 MW
Low	58–275	None	None	2.0–65 MW	2–65 MW

Source: adapted with permission from U.S. Environmental Protection Agency Combined Heat and Power Partnership Program (US EPA CHPP, 2008).

in four strokes of the piston within the cylinder (Hillier and Coombes, 2004; US EPA CHPP, 2008). These are as follows.

- *Intake stroke* – introduction of air (diesel) or air–fuel mixture (spark ignition) into the cylinder.
- *Compression stroke* – compression of air (diesel) or air–fuel mixture (spark ignition) within the cylinder. In diesel engines, the fuel is injected at or near the end of the compression stroke (top dead centre (TDC)) and ignited by the elevated temperature of the compressed air in the cylinder. In spark ignition engines, the compressed air–fuel mixture is ignited by an ignition source at or near TDC.
- *Power stroke* – acceleration of the piston by the expansion of the hot, high-pressure combustion gases.
- *Exhaust stroke* – expulsion of combustion products from the cylinder through the exhaust port.

The air–fuel mixing in a four-stroke gas engine is normally achieved by a suction nozzle and is dependent on the volume of drawn-in air. As the air–fuel mixing is regulated outside, gas engines have longer response times to nominal and actual values of the revolutions per minute (rpm) or the capacity. This should be taken into account, particularly when the engine is operated as stationary and is isolated from the electrical network. High-performance engines are turbocharged to force more air into the cylinders. Technically, the compression ratio in a four-stroke gas engine can be raised from 11 to 12.5 (as with a propane gas engine) by pre-compression of the gaseous fuel (turbocharger) and subsequent cooling of the mixture (Deublein and Steinhauser, 2008; US EPA CHPP, 2008). In this way, the efficiency could be improved by approximately 1–2%. Modest compression is required to prevent auto-ignition of the fuel and engine knock, which can cause serious engine damage.

Four-stroke biogas engines working in CHP plants are equipped with digitally operated spark ignition (Deublein and Steinhauser, 2008). These engines deliver a high-intensity spark of timed ignition and duration to

ignite the compressed fuel–air mixture within the cylinder. This results in low exhaust gas emissions and a long life of the spark plugs (US EPA CHPP, 2008). Moreover, as the ignition is controlled by the microprocessor, the engine can adjust to different kinds of gas and volatile liquid fuel, ranging from propane to natural gas and gasoline or varying gas quality. This is usually accomplished with a proper fuel system, engine compression ratio and tuning. In the case of a biogas-fuelled engine, ignition timing needs to be changed depending on the methane content in the biogas. This is usually monitored through an on-line methane analyser or a knocking monitor (Deublein and Steinhauser, 2008). Using high-energy ignition technology, very lean fuel air mixtures can be burned in biogas engines by lowering the peak temperature within the cylinders (US EPA CHPP, 2008). This will result in reduced NO_x emissions. The lean-burn approach in reciprocating engines is analogous to dry low- NO_x combustors in gas turbines (US EPA CHPP, 2008).

The CO content in the exhaust gas is dependent on the air–fuel ratio. According to European regulations, the CO content in the exhaust gas must be less than 650 mg/Nm^3 (Germany) or 3000 mg/Nm^3 (Denmark). This is usually achieved by cooling the exhaust gas to below 400°C in water-cooled collectors as the oxidation of hydrocarbons to CO (a post-reaction in the tail pipe) is slowed down at these temperatures (Deublein and Steinhauser, 2008). However, the lower temperature brings the efficiency down to 27–35% before the turbocharger (Deublein and Steinhauser, 2008; US EPA CHPP, 2008). Alternatively, a low CO concentration in the exhaust gas can be achieved by using an oxidation catalyst mainly consisting of activated charcoal. An activated charcoal filter located between the suction pipe and the CHP unit will retain catalytic poisons such as siloxanes and sulphur compounds. Thus, the engine efficiency is improved by 3% and emissions of SO_2 (formed by reaction of sulphur and oxygen to SO_2 in the engine) are prevented in the exhaust gas (Deublein and Steinhauser, 2008). In order to prevent engine knock-out with varying gas qualities, a methane content of at least 45% should be ensured (Deublein and Steinhauser, 2008).

All parts of the engine that come in contact with sulphur compounds can be corroded and thus must be protected. To avoid corrosion, specially designed bearings (sputter bearings) should be used instead of normal ball bearings and rings. In addition, special lubricating oils are used, which are low in ash and provide high alkalinity for long periods. These reduce the oil change interval time and considerable wear of the cylinder heads due to the sulphuric acid in the biogas. Finally, CHP units designed for biogas utilisation are generally equipped with large lubricating oil tanks in order to provide high capacity for impurities and the oil will last longer. Depending on the sulphur content of the biogas, regular oil analyses at intervals of 160–

2000 h (on average every 465 h) are compulsory (Deublein and Steinhauser, 2008).

Diesel engines (compression ignition diesel engines) are among the most efficient simple-cycle power generation options on the market. Diesel engines work by direct injection, as combustion in a pre-combustion chamber may develop hot spots, resulting in uncontrolled spark failures with biogas. The quality of fuel injection significantly affects diesel engine operating characteristics, fuel efficiency and emissions. Diesel engines are operated at an air–fuel ratio (λ) of less than 1.9; efficiency is 15% more than that of a four-stroke engine (Deublein and Steinhauser, 2008). However, high temperatures of combustion can lead to an increase in NO_x emissions, while low temperatures of combustion can lead to incomplete combustion and unburnt carbon in the exhaust gas. Depending on the engine and fuel quality, diesel engines produce 5 to 20 times the NO_x (on a ppmv basis) of a lean-burn biogas engine (US EPA CHPP, 2008). However, diesel engines produce significantly less CO than lean-burn gas engines (US EPA CHPP, 2008).

Diesel engines can sometimes knock because of a premature self-ignition of the mixture with high methane content. This problem is exacerbated by the presence of NH_3 in the biogas (Deublein and Steinhauser, 2008), but can be prevented by varying the feed of ignition oil. For instance, when the methane content in the biogas is low, more ignition oil must be added. In the case of an adequate biogas quality, feeding of 10–18% ignition oil is recommended (Deublein and Steinhauser, 2008).

Both mineral oil and vegetable oil can be used to reduce NO_x emissions. However, operation with mineral ignition oil requires special storage. If vegetable oil and/or biodiesel (rapeseed fatty acid methyl ester (FAME)) is used instead of mineral ignition oil, then a leaner air–fuel ratio (compared with the diesel process) can be used. Advantages of renewable ignition oils are lower CO emissions, sulphur-free exhaust and biodegradability. The NO_x emissions from diesel engines burning heavy oil are typically 25–30% higher than those using distillate oil (US EPA CHPP, 2008). The common NO_x control techniques are delayed fuel injection, exhaust gas recirculation, water injection, fuel–water emulsification, inlet air cooling, intake air humidification, and compression ratio and/or turbocharger modifications (US EPA CHPP, 2008). Furthermore, an increasing number of larger diesel engines are equipped with selective catalytic reduction and oxidation systems for post-combustion emissions reduction (US EPA CHPP, 2008).

17.3.4 CHP plants

The use of reciprocating engines (spark plug or compression ignition) is expected to grow in various distributed power generation applications.

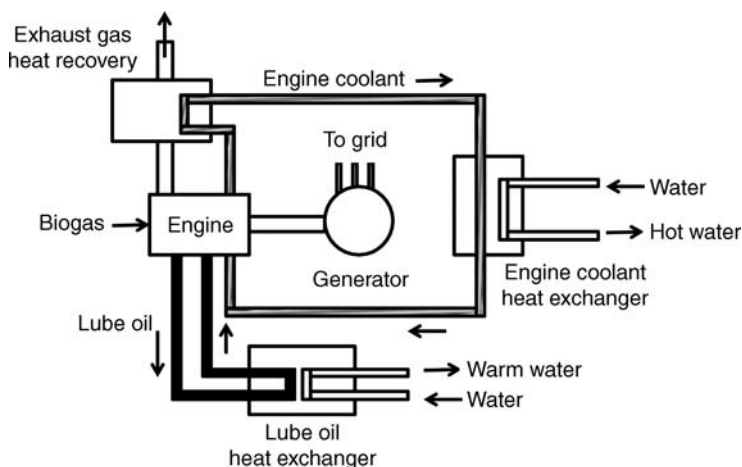
However, the most prevalent on-site simultaneous generation of power and heat for biogas has traditionally been CHP plants and this trend is likely to grow. Approximately 50% of the CHP plants installed in biogas plants in Europe are operated with four-stroke engines and about 50% with ignition oil diesel engines (Deublein and Steinhaue, 2008; Kallio, 2010). Most of the engines can be operated without biogas purification if the level of sulphur compounds is low enough (100 ppmv). On the other hand, some gas motors require more or less upgraded biogas. The total efficiency of modern CHP plants (i.e. the sum of electrical and thermal efficiencies) is within the range 85–90% (Kallio, 2010). Only 10–15% of the energy of the biogas is lost. However, the electrical efficiency (maximum 40%) is still low, and only 2.4 kWh of electric power can be produced from 1 m³ of biogas (Deublein and Steinhaue, 2008). It is thus important that a thermal demand is in close proximity to the facility.

The economics of on-site CHP applications are enhanced by effective use of recovered heat generated by the engine jacket and exhaust gas. Approximately 60–70% of the engine fuel energy can be recovered through this waste heat, for example by recovering hot water for process heat, pre-heating boiler feed water, space heating, anaerobic digester heating and digestate processing. The heat generated in a CHP plant is usually recovered through the exhaust heat exchanger. However, only a part of the heat generated is regained due to high exhaust gas temperatures of 120–180°C (Deublein and Steinhaue, 2008). However, some heat loss in the form of radiation cannot be avoided. Engines with a turbocharger are generally equipped with an intercooler, while gas engines are equipped with a mixture radiator.

Depending on the design, the heat generated in these engines is transferred to the cooling water or to a separate water cycle. The water in the cycle, which transports the heat from the biogas burner to consumers, is normally heated to 90–130°C and flows back to the burner at a temperature of 70–110°C (Deublein and Steinhaue, 2008). One drawback of gas-driven systems is that the engines are said to require much more maintenance than an electric motor. Figure 17.2 shows a CHP system that uses a diesel engine for combustion of the biogas with recovery of heat from the engine coolant, engine oil circulating system and exhaust manifold.

17.3.5 Generation of electricity in a Stirling engine

The principle of a Stirling engine is based on the conversion of thermal energy into mechanical energy (Chambers and Potter, 2002). The Stirling engine is a closed system in which gas or fluid moves inside the engine between cold and heat exchangers. As a result, the engine medium is heated and cooled alternately, resulting in cyclic compression and expansion and,



17.2 Internal combustion engine in a combined heat and power plant generating heat and electricity from biogas (adapted with permission from Chambers and Potter, 2002).

accordingly, changes in pressure of the medium. The changes in the pressure of the gas or liquid inside the engine's cylinders produce mechanical energy, which is converted into electricity using a generator.

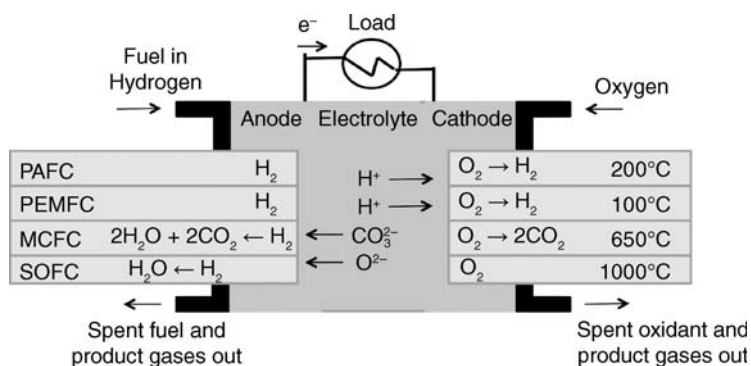
The Stirling engine can use any external heat source (e.g. combustion of biomass or gasoline) and thus it is theoretically ideal for electricity generation from waste heat sources (Chambers and Potter, 2002). It can also use low-quality fuels as combustion takes place outside the engine. Stirling engines are quiet and they are expected to have a long life time.

The efficiency of the Stirling process in conversion from heat energy to electricity ranges from 15 to 30%, with many reporting a range of 25 to 30% (Chambers and Potter, 2002; Scollo *et al.*, 2008). When used in a cogeneration system with heat production and recovery, the overall energy efficiency will be 80 to 85% (Chambers and Potter, 2002).

Stirling engines are available from 1 kW up to 25 kW capacity (Chambers and Potter, 2002). The investment costs of Stirling systems are still high, mainly due to its complexity, and their commercial applications are still limited (Deublein and Steinhaue, 2008). However, there are some development and demonstration projects for Stirling systems with different energy carriers and also in sewage treatment plants for the utilisation of sewage gas (Chambers and Potter, 2002).

17.3.6 Generation of electricity in a fuel cell

Fuel cells generate electricity directly by the electrochemical reaction in which oxygen and hydrogen combine to form water (Deublein and



17.3 Fuel cell types and chemical reactions.

Steinhouse, 2008; US DOE, 2011). Tables 17.4 and 17.5 list the different types of available fuel cells and their advantages and disadvantages. Each fuel cell consists of a negative anode and a positive cathode, which are separated by a solid or liquid electrolyte (Fig. 17.3). Input fuel (e.g. H_2) passes over the anode where it catalytically splits into ions (H^+) and electrons (e^-). At the same time, oxygen (usually from air) passes over the cathode. The ions pass through the electrolyte (electrically non-conductive), while the electrons flow through the external electric circuit from the anode to the cathode. A catalyst, such as platinum, is often used to speed up the reactions at the electrodes. With some fuel cells, the electrolyte is also permeable to oxygen molecules. In this case, the reaction occurs on the anode side. Taking into account all losses, the voltage per single cell is 0.6–0.9 V (Deublein and Steinhouse, 2008). The desired voltage can be reached by single cells arranged in series, a so-called stack. In a stack, the voltages of the single cells are added. Depending on the type of fuel cell, the biogas has to be purified, especially by removing CO and H_2S , before feeding the fuel cell, especially when working in a temperature range up to 200°C (Deublein and Steinhouse, 2008). Methane from the biogas must be reformed to H_2 and fed into the stack. Unused H_2 , that does not pass through the electrolyte is used for the generation of heat through after-burning. At the moment, only a small number of fuel cell plants, mostly pilot plants, are in operation for the generation of electricity from biogas. Fuel cells are considered as small-scale power plants of the future for the production of power and heat with efficiencies exceeding 60% and low emissions (US DOE, 2011).

17.3.7 Generation of electricity in a gas turbine

Biogas can also be used as fuel in the generation of electricity by gas turbines (see Chambers and Potter, 2002; Deublein and Steinhouse, 2008). A gas turbine mainly consists of a compressor, combustion chamber and turbine.

Table 17.4 Comparison of different fuel cell technologies

	Polymer electrolyte membrane (PEMFC)	Alkaline (AFC)	Phosphoric acid (PAFC)	Molten carbonate (MCFC)	Solid oxide (SOFC)	Direct methanol (DMFC)
Common electrolyte	Perfluorosulphonic acid	Aqueous solution of potassium hydroxide soaked in a matrix	Phosphoric acid soaked in a matrix	Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	Ytria-stabilised zirconia	Solid organic polymer polyperfluorosulphonic acid
Operating temperature (°C)	50–100	90–100	150–200	600–700	700–1000	50–100
Fuel gas	Pure H ₂ , methane, methanol	Pure H ₂ , hydrazine	Pure H ₂ , methane, natural gas, coal gas, biogas	Methane, coal gas, biogas	Methane, H ₂ , coal gas, biogas	Liquid methanol
Typical stack size	<1 kW–100 kW	10–100 kW	400 kW 100 kW module	300 kW–3 MW 300 kW module	1 kW–2 MW	Up to 1.5 kW
Efficiency	60% transportation 35% stationary	60%	40%	45–50%	60%	20–25%
Applications	<ul style="list-style-type: none"> • Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles 	<ul style="list-style-type: none"> • Military • Space 	<ul style="list-style-type: none"> • Distributed generation 	<ul style="list-style-type: none"> • Electric utility • Distributed generation 	<ul style="list-style-type: none"> • Auxiliary power • Electric utility • Distributed generation 	<ul style="list-style-type: none"> • Consumer goods • Laptops

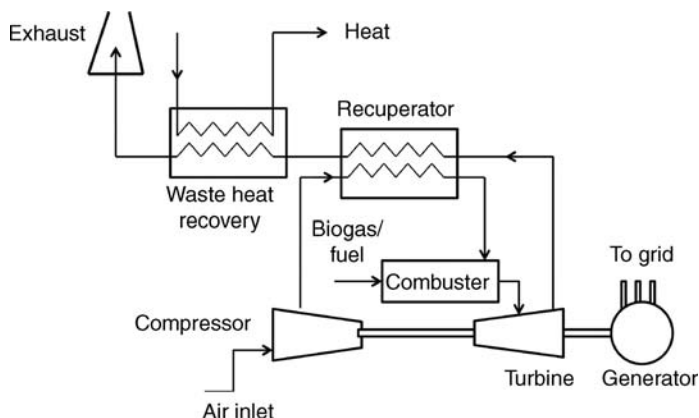
Source: adapted with permission from U.S. Department of Energy (US DOE, 2011); permission granted 10 September 2012.

Table 17.5 Advantages and disadvantages of various fuel cell technologies

Fuel cell type	Advantages	Disadvantages
Polymer electrolyte membrane (PEMFC)	<ul style="list-style-type: none"> • Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up 	<ul style="list-style-type: none"> • Requires expensive catalysts • High sensitivity to fuel impurities • Low-temperature waste heat • Waste heat temperature not suitable for combined heat and power (CHP)
Direct methanol (DMFC)	<ul style="list-style-type: none"> • High energy storage • No reforming needed • Easy storage and transport 	<ul style="list-style-type: none"> • Low power output • Methanol is toxic and flammable
Alkaline (AFC)	<ul style="list-style-type: none"> • Cathode reaction faster in alkaline electrolyte • Higher performance • Low-cost components 	<ul style="list-style-type: none"> • Expensive removal of CO₂ from fuel and air streams required (CO₂ degrades the electrolyte)
Phosphoric acid (PAFC)	<ul style="list-style-type: none"> • Higher overall efficiency with CHP • Increased tolerance to impurities in hydrogen 	<ul style="list-style-type: none"> • Requires expensive platinum catalysts • Low current and power • Large size/weight
Molten carbonate (MCFC)	<ul style="list-style-type: none"> • High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP 	<ul style="list-style-type: none"> • High temperature speeds corrosion and breakdown of cell components • Complex electrolyte management • Slow start-up
Solid oxide (SOFC)	<ul style="list-style-type: none"> • High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte reduces electrolyte management problems • Suitable for CHP • Hybrid/gas turbine (GT) cycle 	<ul style="list-style-type: none"> • High temperature enhances corrosion and breakdown of cell components • Slow start-up • Brittleness of ceramic electrolyte with thermal cycling

Source: adapted with permission from U.S. Department of Energy (US DOE, 2011); permission granted 10 September 2012.

In a continuous cycle, ambient air is compressed in the compressor and transmitted to the combustion chamber, where biogas is introduced and combustion takes place at a maximum temperature of 1200°C (Deublein and Steinhaue, 2008). The produced flue gas is then passed to a turbine, where it expands and transfers its energy to the turbine. The turbine propels the compressor on the one hand and the generator on the other hand to produce power. The exhaust gas leaves the turbine at a temperature of approximately 400–600°C (Deublein and Steinhaue, 2008). The waste heat can be used in a steam turbine downstream, for heating purposes, or for pre-



17.4 Gas turbine process with heat recovery (adapted from Deublein and Steinhaue, 2008, with permission from Wiley-VCH Verlag & Co. KGaA, Germany).

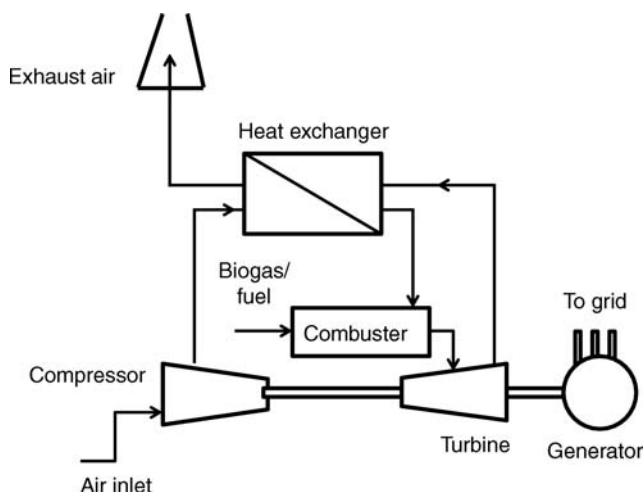
heating the air that is sucked in (Fig. 17.4). Commercial units can range in size from 500 kW to 250 MW. A single-cycle turbine has an efficiency of 20–45% at full load, with efficiency increasing with size (Chambers and Potter, 2002). The electrical capacity, and thus the efficiency of the gas turbine, can be increased by changing the amount of biogas supplied to the combustion chamber or increasing the turbine inlet temperature.

Gas turbines are available in medium to large capacities and are characterised by low emission values. When fed with cleaned biogas, the NO_x emission in the exhaust gas is less than 25 ppmv (Deublein and Steinhaue, 2008). The CO content can be considerably reduced by installing a downstream catalyst.

17.3.8 Generation of electricity in a micro gas turbine

Micro (gas) turbines are small, high-speed, gas combustion turbines with a power rating of 25–500 kW (Chambers and Potter, 2002). Micro turbines are considered easy to handle and are relatively low noise and vibration free. They can use various fuels, including natural gas, biogas, associated gas, biodiesel and kerosene. Micro turbines are increasingly used for biogas applications, especially in cogeneration at wastewater treatment plants, codigestion plants, farms and landfills.

Micro turbines typically comprise an air compressor, combustor, turbine, alternator, recuperator and generator (Fig. 17.5). Micro turbines have a single shaft on which the compressor, turbine and generator are fixed. Gas turbines are single-stage, radial flow devices with rotating speeds of 90 000 to 120 000 rpm (Chambers and Potter, 2002). The turbine propels the



17.5 Micro gas turbine process with heat recovery (adapted from Deublein and Steinhauser, 2008, with permission from Wiley-VCH Verlag GmbH & Co. KGaA, Germany).

compressor, which compresses the air and, at the same time, the generator (Deublein and Steinhauser, 2008). In micro turbines, the compressor draws the air into a recuperator, which acts as an air-to-air heat exchanger, recovering the heat from exhaust gas. Heating of the combustion air increases the micro turbine's electric efficiency. The heated air is passed into the combustor chamber, into which fuel is also injected. For biogas applications, the minimum methane content in the biogas should be 30%. In the combustor chamber, the combusted mixture expands, which in turn causes the turbine and shaft to rotate and thus generate electricity.

Micro turbines are generally regulated by varying the fuel supply. The electrical efficiency of micro turbines is typically 15–30%; the higher range efficiencies are obtained with pre-heated combustion air (Chambers and Potter, 2002; Deublein and Steinhauser, 2008). Micro turbine exhaust temperatures are relatively low (about 200–300°C) and the waste heat can only be used to generate low-pressure steam and/or hot water (Chambers and Potter, 2002). Electrical efficiencies up to 50% are achieved when a micro turbine is coupled with a micro steam turbine.

Micro turbines are more expensive than traditional gas engines, but their maintenance requirements are much less and thus maintenance costs are reduced. Their life time is also relatively long. The maintenance interval ranges from 2000 to 8000 h, but can be longer if the turbine is operated above the normal operating temperature of approximately 10°C (Deublein and Steinhauser, 2008). Like large gas turbines, micro turbines are tolerant to humidity and corrosive gases in the fuel gas as long as condensation is

avoided in the fuel delivery system. They also have better resistance against sulphur compounds and lower exhaust emissions.

17.4 Conclusion and future trends

Biogas is produced during the anaerobic digestion of organic materials from industry, municipalities and agriculture. The produced biogas is considered a versatile renewable energy source and can be converted to heat and/or electricity. However, biogas needs pre-treatment depending on the biogas composition and equipment used. There are several commercially available systems for treating biogas and utilising the cleaned biogas to produce heat and/or electricity in stationary applications. Typically, biogas pre-treatment involves the removal of foam, particulate matter and water vapour along with H_2S (<100 ppmv) and siloxanes.

Biogas power generation in stationary applications includes internal combustion (IC) engines such as four-stroke spark ignition and diesel engines, gas turbines, micro turbines, Stirling engines and fuel cells. However, the total efficiency of equipment is dependent on the fuel conversion capability. The conversion efficiency for IC engines is 25–42%, for a Stirling engine, 25–30% and for a micro turbine 15–30%. However, the most prevalent on-site simultaneous generation of power and heat for biogas has traditionally been CHP plants. In CHP mode, there is not a great difference in the total energy conversion efficiency (85–90%) for the range of conversion options. However, the total CHP efficiency to electricity is dependent on size and power-to-heat ratio and varies from one type of equipment to another. IC engines (both four-stroke spark ignition and diesel engines) can be coupled with a generator to produce electricity. The overall efficiencies of 80–90% are achieved as heat can also be recovered, both from the exhaust gas and from the engine cooling system. Similarly, micro turbine or Stirling engine based CHP units have efficiencies of 85–90%. Fuel cell technologies may achieve total CHP efficiency in the 65–75% range depending upon the technology.

Other factors influence the choice of equipment, particularly investment and maintenance costs, reliability and exhaust emissions. Total installed costs for gas turbines, micro turbines, reciprocating engines and Stirling engine are comparable. The total installed cost for a typical gas turbine (5–40 MW) ranges from €900/kW to €1500/kW and micro turbines in grid-interconnected CHP applications range from €600/kW to €1200/kW. Similarly, commercially available gas engines have total installed costs of €400/kW to €1100/kW. Fuel cells are currently the most expensive of the existing CHP technologies with total installed costs ranging between €3000/kW and €4000/kW. Operation and maintenance (O&M) costs typically include routine inspections, scheduled overhauls, preventive

maintenance and operating labour. O&M costs are comparable for gas turbines, micro turbines, gas engines and fuel cells, and only a fraction lower for Stirling engines. Total O&M costs range from €0.005/kWh to €0.010/kWh for typical gas turbines and from €0.010/kWh to €0.02/kWh for commercially available gas engines. Based on manufacturers' service contracts for specialised maintenance, the O&M costs for micro turbines are €0.008/kWh to €0.015/kWh and between €0.003/kWh and €0.01/kWh for fuel cells.

Micro turbines are already commercially available while Stirling engines are still mainly in development phase. Both promise much lower NO_x and CO emissions and maintenance costs. Compared with traditional gas engines, micro turbines have better resistance to sulphur compounds and lower exhaust emissions but are more expensive. Fuel cells are often considered to be the small-scale plants of the future for the production of power and heat with efficiencies of 65–75% and extremely low emissions (3 mg NO_x/Nm³ flue gas).

Micro turbines have become a popular alternative to IC engines due to their lighter maintenance schedule, lower noise levels and lower air emission levels. The initial cost is higher, however. Fuel cells may be an option in the future, but costs need to come down before they become a practical alternative for farm use. Micro turbine or Stirling engine based CHP units are just now becoming commercially available. Both promise much lower maintenance costs as oil changes are not required. Currently, the capital cost of these options is still over 60% more than IC engines, but these costs are predicted to drop dramatically with time and increased production of the units.

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Abstract: This chapter describes the fundamentals, potential and synergy of jointly using biomethane and natural gas in the transport sector. In the absence of an extensive national gas grid, biomethane distribution logistics of liquefied biogas (LBG) or compressed biogas (CBG) by road is capital intensive; however, biomethane represents an opportunity to make the natural gas vehicle (NGV) market green, forming a virtual gas grid. The promotional value of biomethane may offset some of the extra costs, particularly so when contemplating a future paradigm shift towards a fully sustainable society. The status and growth prospects of the Swedish and the world NGV market are described and discussed. Gas quality issues and relevant vehicle technology developments are also covered.

Key words: biomethane, natural gas vehicle (NGV) market, virtual gas grid, sustainable society, Sweden.

18.1 Biomethane as a transport fuel

The need to counter pollution and climate-influencing emissions from energy generation and utilization is acute. Many avenues are available regarding heat and power, but a tougher challenge is finding a replacement to counteract the almost total oil dependency of our transport system. Besides minimizing our transport needs, the transport system needs to become more energy efficient and be based on a higher proportion of renewable fuels. Biomethane is a high-quality energy carrier, fully miscible and interchangeable from a combustion point-of-view with its fossil counterpart natural gas. This is not the case for other biofuels. It is a gaseous drop-in fuel with no blending limitations and end-user complications, if sufficiently purified. Of the second-generation biofuels, biomethane

is comparatively less dependent on specific technical developments, less dependent on scale of production, has a greater feedstock flexibility and potential, and can be integrated into the natural gas distribution network (Åhman 2010). Apart from renewable electricity, the regulated and unregulated emissions of biomethane, together with its carbon footprint, are lower than for all other biofuels. In contrast to electric vehicles, the natural gas vehicle (NGV) market is fully mature and ready to deliver given the proper incentives, inclusive of long-distance road transport within the next few years, through implementation of liquefied natural gas (LNG) and dual-fuel technology. The climate benefit of using biogas in combined heat and power (CHP) schemes replacing coal may be theoretically better than replacing fossil transport fuels, but full utilization of the produced heat is highly unlikely, especially during the summer. Also, the argument must be made as to why would we waste a high-quality energy carrier such as biogas on electricity production, when the oil dependency of our transport systems needs to be solved today, not in a distant, uncertain future? It is argued that the large-scale use of biomethane has been wrongfully overlooked in studies focusing on long-term and large-scale options for the transport sector (Åhman 2010).

18.1.1 Hydrogen and the future gas engine

Hydrogen has for decades been hailed as the answer to all of the problems of the current oil-dependent transport industry. However, the technical challenges have so far been too steep to overcome. Recent developments with respect to fuel cell technology and hydrogen production may change this. Major vehicle manufacturers such as BMW and Toyota are planning to launch fuel cell powered vehicles before 2020. Reverse fuel cell technology may make it possible to produce hydrogen from surplus wind electricity at higher yields compared with traditional electrolyzers.

It is very likely that fuel cells and e-mobility will be important players in future transport systems in order to meet the challenges of energy efficiency, increased renewability and climate change mitigation. However, the challenge of transforming transport needs to start right away; the technology of NGVs is commercially available today for all types of vehicles and all types of distances. The needs of the heavy-duty vehicle (HDV) market will be fulfilled in the short-term through fuel-efficient methane diesel engines and space-efficient on-board storage of liquefied methane. In addition, mid-term engine developments such as exhaust gas recirculation (which improves low-load performance), high-energy ignition systems (which increase the dilution limit) and better detection and control of the calorific gas quality will make it possible to attain diesel engine efficiency in future NGVs. The relative efficiency gain of hybridizing the

methane powered Otto engine is higher compared to its petrol counterpart. In addition, hybridization of the NGV powertrain will make it possible to decrease the fuel storage size, effectively taking away a large part of the NGV markup cost and payload penalty.

18.1.2 Gas quality: the effect of trace compounds on NGVs

Technical developments in the form of cryogenic upgrading have made it possible to clean landfill gas to biomethane quality. Stricter emissions standards for vehicles have led to a higher level of sophistication in engine and after-treatment technologies and have made it necessary to better control the trace elements levels of biomethane. Of particular concern are siloxanes. Siloxanes are suspected to be accountable for many of the undiagnosed operational problems in NGVs, since they precipitate as solid silica during combustion. Problems with lambda sensor clogging have been attributed to the presence of elementary silicon in petrol. It is unknown whether similar problems might arise from the presence of siloxanes in compressed biomethane. There is undoubtedly a risk that the formed silica will precipitate in after-treatment systems, an accumulative effect that leads to more rapid deactivation and aging of the catalyst.

With respect to microorganisms, there is much discussion on the potential health and pipeline integrity hazards of introducing biomethane to the natural gas system. In fact, the levels of microorganisms are just as high in natural gas as they are in biomethane. For vehicle gas, it is likely that the combined effect of heat development during compression, drying of the gas and filtration with 0.2–1.0 micron filters is sufficient to make the compressed gas quite disease vector free. In addition, Vinnerås *et al.* (2006) claim that the amount of biomethane needed to inhale to become infected (even with severe pathogens, which were not found in the study in question) is so large that the risk of accidental fire and suffocation is much more pronounced. A very small amount of gas is released during refueling, approximately 5 cm³. Thus, if pathogens were present, then the absorbed dosage would be too small to constitute any real risk.

In addition to the biologically derived trace elements it is also evident that there is a need to regulate more closely the contents of water and entrained compressor oil. The fact is that most of the operational problems of NGVs may be attributed to elevated levels of these two substances. These problems will not lead to engine failure, but do lead to reduced drive performance and erratic service. All of these problems may easily be controlled by properly addressing the removal of water and oil in the compressed gas. In winter climates, if the water level is not kept sufficiently low, the expansion cooling that occurs when the gas flows from the storage tank through the vehicle's fuel system may lead to the formation of intermittent hydrocarbon hydrate

plugs. To avoid this problem, the gas industry in Sweden dries compressed natural gas (CNG) by lowering the temperature to -80°C at 4 bar, corresponding to a removal of water down to a level well below 1 mg per Nm^3 . Entrained compressor oil in NGV engines may cause operational problems with pressure regulators and gas injectors. Another important aspect is to manage any vehicle incompatibility issues regarding the oil itself or any of its additives. Oil levels need to be monitored and controlled through oil removal downstream of the compressor. The developed practice of maintenance is to have two oil coalescing filters in series, one close to the compressors and one as far away as possible in order to allow for the cooling of the gas, leading to precipitation of the dissolved oil.

Another important trace compound that is relevant for both biomethane and CNG is the content of total sulfur. Lowering the maximum level for total sulfur content is important because the high content of sulfur dioxide in exhaust gases has an inhibitory and aging impact on catalysts, with lean-burn engine applications being the most sensitive. It is clear that most of the sulfur has its origin in the odorization agent added, with THT (tetrahydrothiophene) being the most common (typically 15 mg is added, corresponding to 6 mg S/ Nm^3 ; more is added in markets such as in France, Spain and Italy). More sulfur-poor and even sulfur-free alternatives are available on the market, although the sulfur-free option is a less likely candidate, due to its uncharacteristic odor.

The state of standardization is not satisfactory for CNG in general and renewable compressed biogas (CBG) (biomethane) in particular. Standardization at the international level is mostly qualitative. Most standards are at the national level and, with the exception of Sweden, biomethane is only standardized for injection into the natural gas network. A mandate (M/475, 2010) from the European Commission to develop CEN standards for biomethane fed into the grid, or used directly as renewable CBG, has changed this, and work is ongoing in a new committee (CEN/TC408 Project Committee – Biogas for use in transportation and injection into natural gas pipelines). The work started in autumn 2011 and is scheduled to finish in 2015. A variety of trace elements is under discussion for inclusion in the new standards; a new development has led to CNG also being included in the scope, finally leading to quantitative standardization at international level for all methane-based vehicle fuels.

18.2 Biomethane distribution logistics and the synergies of jointly used natural gas and biomethane

Depending on the location and type of upgrading, the upgraded biomethane may be distributed in several ways: by injection to a central or local gas grid or by road in mobile units, either in compressed or liquefied state. Used in an optimized manner, all of these have a role to play in reaching full utilization of the available biomethane potential. Methane being a major component in biomethane and natural gas makes joint distribution and utilization of natural gas and biomethane a natural step, which has been shown through market experience to give rise to several synergies. These aspects are covered in this section, which is an excerpt from a NGVA position paper written by the author (Svensson 2010).

18.2.1 The benefits of injecting biomethane into the natural gas transport network

Biogas upgraded to natural gas quality is injected into existing gas grids across the world. IEA task 37 lists 221 upgrading facilities on their homepage (December 2012), and a majority of them inject the generated biomethane into the grid (Petersson and Wellinger 2009). Grid transport is one of the most energy-efficient and environmentally friendly ways to transport energy (Papadopoulos 2009). In countries with extensive natural gas grids such as the Netherlands (around 90% plus connectivity of houses to the gas grid) and Ireland (48% of all houses connected to the grid), gas grid injection is the optimal solution for the distribution of biomethane (Thamsiriroj *et al.* 2011). In addition, the produced biogas is fully utilized, thus avoiding unnecessary flaring or other losses such as underutilization of the heat in CHP generation.

Since natural gas and biomethane can be intermixed freely and are fully interchangeable, virtual distribution networks of ‘green gas’ are easily implemented; this is often referred to as utilizing the green gas principle, a direct reference to the established concept of green electricity. The principle is the same, irrespective of distribution distance and type, spanning from the CO₂⁻ neutral cycles of local distribution networks, where the biomethane is produced, upgraded, injected and utilized in the same area, to the still not realized option of selling the injected gas abroad, disregarding actual physical transmission capacity. Accounting of the produced and subsequently sold biomethane can be done in the same way as with green electricity. Green gas systems are already in existence, either in the form of distribution companies’ own internal accounting, such as in Sweden, or by

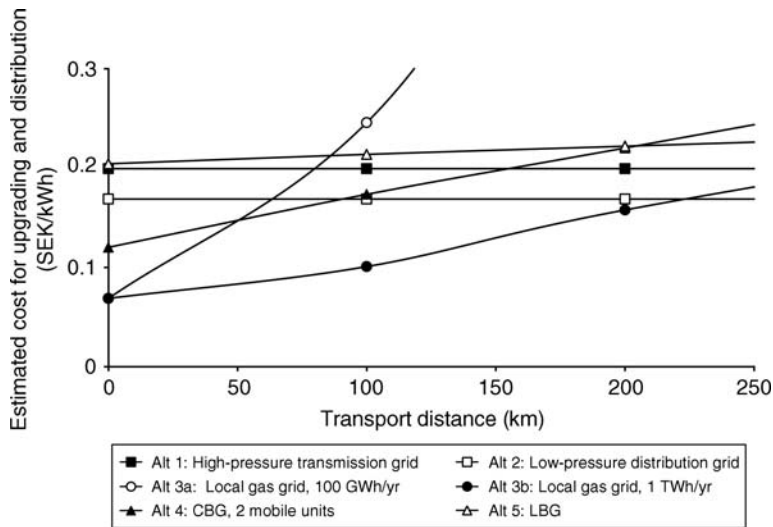
way of an independent certificate trading company or body, such as is in Holland (www.vertogas.nl) and Switzerland (Kornmann and Wellinger 2009).

From a technical viewpoint, biomethane grid injection is established and uncomplicated. Issues remaining to be addressed are related to feed-in regulations and economy. It is important to deliver a gas quality within specification to customers. Most grid injection so far has been in low-pressure distribution lines, close to the customer. If it is necessary to meet a higher heating value specification, as is the case with H-gas quality in certain parts of the European gas grid and the Danish gas used in Sweden, it is sometimes necessary to add propane. This, of course, incurs an extra cost. Renewable ethane or propane can be synthesized from biomass-based glycerol in a catalyzed process in a financially feasible manner and cleaned of CO₂ together with the biogas in the upgrading unit of the biogas plant (Brandin *et al.* 2008). In most of Europe, the mixing of gases with different gas specifications is already done at large scale. Here, it would be better to inject biomethane before the mixing points into high-pressure transmission lines. This solution would also circumvent the potential problem of lower customer demand during the summer, effectively lowering the maximum amount of biomethane allowed to be injected into that particular distribution area.

The investment costs associated with upgrading and subsequent grid injection, together with the necessity of adding propane or high pressurization work, can be economically prohibitive for individual biogas plant owners. However, from a societal point of view, the benefits of increasing the availability and utilization of domestic gas production are obvious, and it has been suggested that upgrading and injection of biomethane should be an integral part of grid infrastructure management, the costs thus being shared by all gas customers (EP ITRE 2008a, 2008b, 2008c; European Commission 2009; SEI 2009).

18.2.2 Distribution solutions far from the natural gas transport network

Far away from the national natural gas transport network, other biomethane distribution solutions come into play; for example, by road in mobile storage units, either in compressed or liquefied state, or by laying down local gas lines. A report issued by the Swedish Gas Association shows the relation between transport distance and transported volumes for the different upgrading and distribution alternatives available on the market (Benjaminsson and Nilsson 2009). The results are summarized in Fig. 18.1. For short to medium distances and larger volumes, local gas grids provide the best alternative. Considering road transport, compressed vehicle



18.1 Comparison of costs (SEK/kWh) between transport distance (km) and transported volumes for different upgrading and distribution alternatives at 100 GWh/yr. Alt 1, high-pressure transmission natural gas network; Alt 2, low-pressure distribution natural gas network; Alt 3a, local gas grid, 100 GWh/yr; Alt 3b, local gas grid, 1000 GWh/yr; Alt 4, CBG, 6000 Nm³/truck; Alt 5, LBG, 35 000 Nm³/truck. Note that the extra costs of cryogenic upgrading are included. For reference, the costs of transport in national transmission and distribution network are also included; the gas replacement benefit of biomethane injection is not included in the estimate, which would otherwise decrease the costs (© Grontmij Sweden, Benjaminsson and Nilsson (2009)).

gas¹ (CNG for short in line with internationally agreed road signage) is the best option for all volumes up to distances of 200 km as compared with liquefied vehicle gas (or liquefied natural gas LNG²), which has higher investment costs but much lower transport costs. However, it should be noted that the handling of CNG mobile units (Fig. 18.2) when dealing with higher volumes is a logistical challenge.

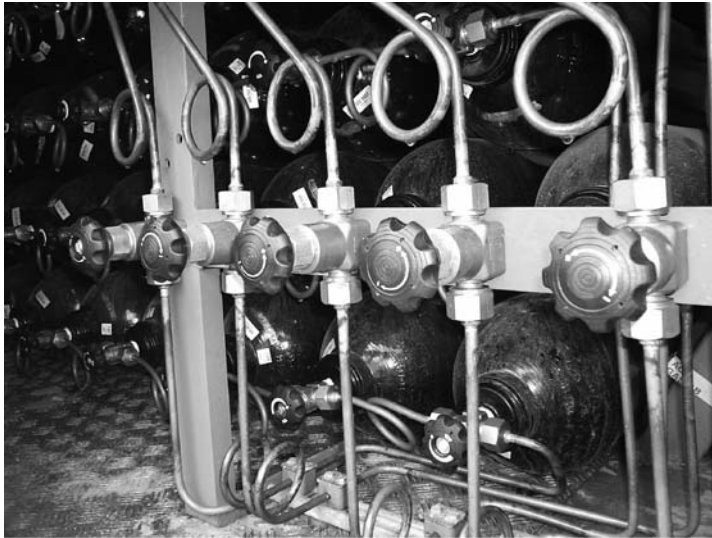
An added advantage of local biogas grids is, of course, the creation of new opportunities for biomethane injection along the entire length. Since current commercial upgrading processes need to be of a certain size to be economical, it is a good idea to supplement the grid with a parallel raw biogas grid, collecting and transporting the biogas from several smaller biogas plants to a central upgrading facility. In this way it is possible to realize the potential of agricultural biogas, which is quite disperse in nature,

¹ In Sweden, the term vehicle gas is a common designation for all methane-containing gases, irrespective of origin.

² The term used on internationally agreed road signage, irrespective of the origin of the fuel.



(a)



(b)

18.2 Compressed natural gas mobile units are handled with hook lift trucks and represent a virtual grid supply for refuelling stations far from the natural gas grid or biomethane production plants. Figure 2(a) © FordonsGasSverige AB. Figure 2(b) courtesy of J. Murphy.

and avoid the construction of a centralized facility with its inherent disadvantage of transporting large volumes of substrate and digestate.

Liquefied biomethane at -162 to -130°C (at 0–8 bar overpressure), generated through either dedicated cryogenic upgrading or liquefaction of conventionally upgraded biogas, is the latest biomethane distribution state. With an energy density comparable to CNG at 600 bar (around. 22.7 MJ/l or 6.3 kWh/l), and carried in less heavy containers, the transport economy of LNG is five times better than for CNG at 260 bar in type-1 steel cylinders. The extra liquefaction costs are quickly compensated for by increased economical transport range and less cumbersome transport logistics. An additional benefit is the lowered operational costs in the refueling stations. Strategically placed mother stations with both LNG and CNG refueling capability may supply surrounding daughter CNG stations through CNG mobile units, effectively creating a virtual grid type of distribution. When re-gasifying the LNG, some of the energy spent on liquefying the methane is regained, since it takes much less energy to pressurize a liquid than a gas. In addition, several synergies exist with LNG utilization in maritime shipping and industry.

An additional way of generating LNG directly from the natural gas grid is by way of utilizing expansion work in the measurement and regulation stations of the gas grid for liquefaction and electricity generation purposes. Depressurizing from 60 to 4 bar, the electricity generated is sufficient to fully sustain the liquefaction plant, providing enough cooling to divert as much as 30% of the total stream as LNG (Pettersson *et al.* 2006). Using the green gas principle, this out-take of LNG can be sold as renewable methane.

18.2.3 Synergies of joint distribution and utilization of biomethane and natural gas

The synergies of joint distribution of biomethane and natural gas are quite obvious. It is the same molecule, so allowing biomethane to utilize the natural gas transport infrastructure decreases the total costs and makes it possible to reach full utilization of the energy of the biogas potential (Thamsiriroj *et al.* 2011). At the same time, the renewability of the energy gas infrastructure is increased.

When the natural gas grid distribution system is not an option, several synergies are at hand when allowing for joint utilization of natural gas and biomethane for automotive fuel purposes. The irrefutable environmental benefits of biomethane make it the preferred choice at all times, but in an emerging market situation its production is too insecure and small to adapt smoothly. Here, natural gas can not only initiate and accelerate market penetration during the build-up of the biomethane production capacity and

hence facilitate the unavoidable hen-and-egg situation, but can also serve as a backup and secure supply source in the event of production failures or sudden growth in demand.

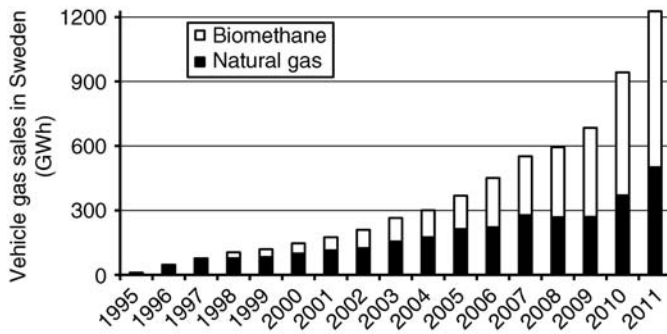
The Swedish NGV market is a showcase for this type of synergy. Gas grid coverage is limited to the west coast of Sweden, making it necessary to utilize biogas as the main source of gas in the rest of the country. Natural gas in compressed and liquefied form is used as backup to sustain the biomethane market development. At times of accelerated market expansion, the use of natural gas may increase for a time, but customer preferences motivate the gas suppliers to strive for a growing share of renewable methane, even in the parts of Sweden with natural gas grid access. Over time, the volumes of biomethane on the Swedish NGV market have continually increased, in 2011 reaching 60% on an energy basis in a total market of more than 1200 GWh, supplying 38 600 vehicles, of which a significant portion are buses.

Road transport of biomethane should be avoided for larger volumes because grid transport is so much better in terms of both costs and energy expenditure. This is addressed by investing in local gas grids. The expansion and connection of local grids to the national grid is a natural progression in an expanding biomethane market, once again showing the importance of natural gas and biomethane working together in the same market.

It can be envisaged that LBG will change the market conditions in a very positive manner for countries with conditions similar to Sweden. The three types of distribution – by grid, LNG by road and CNG by road – will co-exist, fulfilling different needs of the market.

18.3 Growth of the natural gas vehicle market in Sweden

The emergence of a prolific and highly renewable Swedish NGV market has its origin in the fact that Swedish energy supply has become more and more renewable over the past 40 years. Swedish needs for heat and electricity are well covered by renewable and nuclear sources instead of fossil fuel. Only the transport sector remains dependent on fossil oil-based fuels. There was thus no real incentive for natural gas to become a primary solution for residential heating needs and its distribution is restricted to a grid established along the south west coast of Sweden, with consumption dominated by industry and, more recently, large-scale CHP applications. From a Swedish political viewpoint, natural gas is a fossil fuel (not significantly differentiated from oil and coal) and the grid has not been allowed to grow nationally. A strong lobby from solid biofuels actors has also been an important factor in this context. Thus, the national certificate



18.3 With a share of 60% renewables and a total market of 1228 GWh in 2011, Sweden has the greatest sales of biomethane in the world, both in absolute and relative terms, despite only representing a hundredth of the total Swedish road transport market.

system for renewable electricity in Sweden is a magnitude lower than that in Germany, which specifically targets electricity production at farm-scale level from anaerobic digestion. The energy policy instruments with regard to renewable energy in Sweden are weaker and more general in character compared to those of, for example, Denmark and Germany, leading to a situation where more ready-at-hand and cost-efficient solutions such as centralized co-generation of heat and electricity from low-cost forestry residues are preferable to smaller scale biogas CHP applications with more limited profitability.

The Swedish NGV market had its starting point in the early 1990s when the gas companies, looking for new market segments partnered with municipalities who wished to convert their bus fleets to gas in order to diminish local environmental pollution effects and, later, to mitigate climate change through waste-based biomethane production schemes. The market growth was incentivized by state programme investment funds for the municipalities, which were in effect for more than a decade. Out of 5 billion SEK of available funds, 12% was allocated to biogas projects. With the aid of the state programme funding, municipalities without access to natural gas had the opportunity to do the same thing as the grid-connected municipalities who had started using natural gas in their city buses. These prime moving municipalities, in their turn, took the chance to fulfill their environmental goals by implementing biogas upgrading technology and using a mix of biomethane and natural gas in their vehicles. Thus, the growth of the NGV market also led to a steady growth of upgraded biogas utilization, as illustrated in Fig. 18.3. by the volumes of biomethane outstripping the volumes of natural gas utilized. In 2009, the biomethane share reached a peak of 60% of the total market; this level was maintained

for three years in a row, even though the total market doubled during the same period.

The successful building of the current Swedish NGV market (1% of the total road transport market) and its high proportion of biomethane use was made possible by the joint efforts of public and private actors. Regional platforms of public–private partnerships promoting NGVs and biomethane have been and still are instrumental in development and promotional work. These local and regional efforts were incentivized by the ambitious environmental goal programme of the state, assigned to public actors to fulfill. An important tool was the regional and local government procurements that created long-term demand for increasing shares of renewable fuels in all types of vehicles contracted by the public, such as taxi services and buses. The bus market is still the single most important market, covering approximately 50% of the sales volumes. It has been shown that the bus fleet operators provided the essential niche for the growth of the emerging market of gas-powered vehicles in Sweden, facilitating the later introduction of a larger and more diversified market (Sandén and Jonasson, 2005). The joint vision of the four largest regional government actors and the national association in eventually reaching 100% renewability shows the necessity of providing more and more renewable methane in order to meet customer expectations. The most ambitious actor is the public transport authority in the south, Skånetrafiken, which is converting the buses in its intercity bus segment (Fig. 18.4).

There were 1529 gas buses on the road in Sweden in 2011; 600 of these were deployed in Skåne, 200 in Stockholm, 200 in Gothenburg and surroundings (Västtrafik) and 158 in Linköping/Norrköping and surroundings (Östgötatrafiken). Numbers are still increasing: national bus operator Keolis have ordered 433 new buses for delivery by summer 2012.

In addition to state funding over the years, the Swedish NGV market has enjoyed the benefits of several market incentives such as investment grants for refueling stations and free parking. Still in force and most important are tax exemption (until 2013) and the fringe benefit taxation reduction for company cars (around 900€ per year until the end of 2012). Quite a large share of light-duty vehicles (LDVs) has been introduced to the NGV market through this route. All new eco-labelled LDVs are exempt of vehicle tax for a period of 5 years after purchase; this policy has turned out to impact diesel-powered cars, since their vehicle tax is very high, while the tax on NGVs is already quite low. Today, however, the largest concern of the market players is lack of long-term commitment in government policy. The beneficial policies are unsecure or low and there is a lack of tools to meet the national grand vision of a fossil-free transport sector in 2030.



18.4 Public buses are the most important NGV market segment in Sweden, with a share of 11% of all registered medium-duty and heavy-duty buses. The public transport authority in the south of Sweden, Skanetrafiken, has the largest number of NGV buses, with the ambition to become fossil free by 2020. The conversion of its city bus fleet is almost complete and work has also come a long way in the intercity bus segment. The long-term commitments of the Swedish Public transport authorities are important collaterals in new biomethane investment schemes (© Swedish Gas Technology Centre, www.sgc.se).

18.4 Extent and potential of the natural gas vehicle world market

The world NGV market in 2011 comprised 14.5 million vehicles of all classes. The top ten markets are dominated by LDVs, which to a large extent are aftermarket conversions. The light-duty NGV market in these countries is usually driven by the large price difference between natural gas and gasoline. Diesel is often subsidized, which makes HDV applications less interesting when the fuel cost advantage of natural gas is taken away. With the exception of Italy, which has the longest unbroken use of NGVs in the world ever since their emergence in the 1940s, the big markets are found outside Europe. European governments do not use fuel subsidies to boost their national markets, but instead have rather high taxation levels on fossil petroleum fuels, with some exceptions for diesel in some market sectors. Consequently, HDVs are more prevalent, especially if local emissions are an issue. Thus, captive bus fleets play a major role in many countries. With gas consumption corresponding to 20–30 LDVs, even a small proportion of

buses will dominate the market, as is the case in countries such as Spain, Sweden, France and Turkey. Higher utilization of the refueling infrastructure in dedicated bus depots, together with the needs of urban areas to decrease local air pollution from transport, are the main reasons why this market sector tends to crop up as a prime mover in the emerging NGV market situation in the European context.

The last decade turned the NGV market into a growth business. Between 2001 and 2007, annual world growth was 26%, increasing from 1.7 million vehicles to 7 million. From 2007 to 2011, annual growth decreased slightly to 20%, with the total number of vehicles at the end of 2011 standing at 14.5 million. A conservative estimate of 18% annual growth would mean that the world NGV market would reach 65 million vehicles in 2020, which is a goal set by the International Association of NGVs (www.iangv.org, www.ngvglobal.com). This would correspond to a 9% vehicle market share, and a market of 400 billion cubic meters per year would correspond to 12.5% of the 2010 natural gas market (www.iangv.org, www.ngvglobal.com).

Biomethane is still playing a marginal role in this growth, but increasing interest is evident; demonstration projects have been set up all over the world, including India, Canada, Thailand, Estonia, China, New Zealand, South Korea, South Africa and Brazil. More mature market introduction of biomethane as a drop-in fuel in the existing NGV market is mostly Europe based, with one exception in the USA, where one third of the refuse truck operation of the 1000 NGVs of the company Waste Management is powered by biomethane from the Altamont landfill in California (roughly corresponding to 100 GWh). Sweden is at the forefront, both in relative and absolute terms, with its 60% share of biomethane in a 1.2 TWh market. The total share of biomethane at a world level is still erratically reported, leading to a very rough world estimate of 1–3 TWh per year. European statistics for 2011 from NGVA Europe (www.ngvaeurope.eu) places Sweden at the top (726 GWh) with the other European countries amassing roughly a third of that; the second major player in Germany, with a blending rate of 21% (183 GWh). However, countries such as the UK, Holland, Spain and Austria – known to be using biomethane – have not reported any figures.

18.5 Future trends

The future of biomethane looks bright, especially when derived from waste. All over the world the vast amounts of biowaste coupled with increasing needs for climate change mitigation, local air pollution control and oil dependency abatement give rise to a waste management solution through biomethane production. This is especially pronounced in countries where local or regional governments are in charge of both waste management and

the running or procurement of public transport. In EU 27 alone there is a waste potential of 500 TWh – capable of powering 2 million city buses.

It is quite costly to produce natural gas quality biomethane for vehicle fuel purposes, especially in countries where natural gas, petrol and/or diesel is subsidized or lightly taxed. Infact, natural gas is the most adverse competitor of biomethane, especially with the price falls of recent years. Nevertheless, given the proper incentives by government, based on external costs such as public health, environmental hazards and subsidy costs, the market potential is there. The promotional value of biomethane should not be underestimated. With the need for climate change mitigation and the aims of a truly sustainable society, the extra cost of blending in biomethane, especially if it is tax exempted for the longterm (preferably up to a certain market share rather than a specific date), will be covered by the extra sales gained from green natural gas. The Swedish case may serve as an example of how public opinion can affect the building of a natural gas vehicle market in a society more and more inclined to promoting renewable and sustainable solutions, and banning or taxing fossil fuel powered alternatives.

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Market development and certification schemes for biomethane

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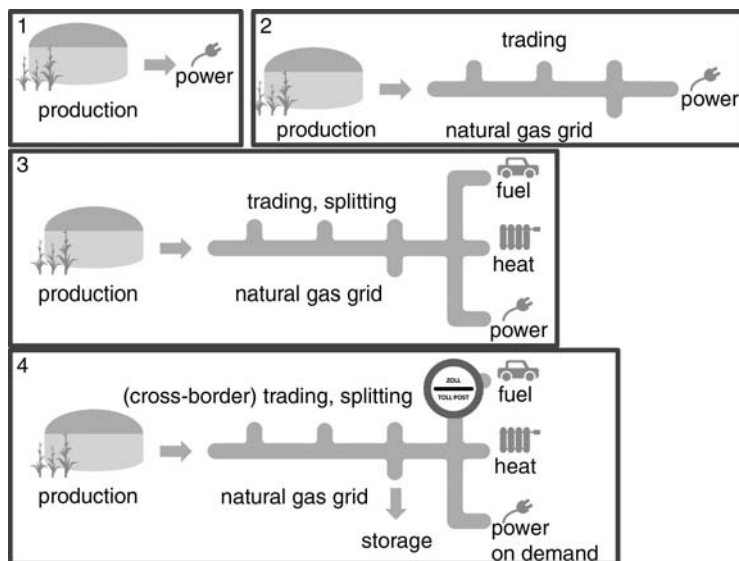
DOI: 10.1533/9780857097415.3.444

Abstract: Upgrading of biogas to methane and subsequent feed-in to the gas grid makes biomethane the ‘joker in the pack’ in the renewable energies game, with advantages from environmental, political and economic points of view. Thus, in many countries, governments have designed national support schemes or announced national targets, resulting in development of the biomethane market. Feed-in support schemes, quota obligations and green gas products are the dominating market drivers in Europe. While most countries base their production on organic waste as feedstock, Germany dominates Europe’s feed-in market with energy crops; its market has developed rapidly, from first feed-in in 2006 to a total of 80 plants operating at the end of 2011. The main driver in Germany is the feed-in tariff for renewable electricity via the Renewable Energy Sources Act (EEG). European trading of biomethane was enabled by European directives. Support schemes for biomethane rely on mass balancing systems or ‘book and claim’-certificates. Several mass balancing systems have developed in Europe, such as the German Biogasregister Deutschland and the Dutch Vertogas. Discussion on the impacts on the agriculture, rising government awareness of biomethane and the removal of barriers for international trade will be trends for the coming years. Existing mass balancing systems may contribute to international market development by creating a common standard. System integration into gas and power grids, moving from subsidies to markets and competition with natural gas may become issues when biomethane increases in relevance.

Key words: biomethane, feed-in, mass balancing, certification, biomethane markets, Biogasregister Deutschland.

19.1 Introduction

Upgrading of biogas to biomethane and feed-in to the gas grid has important advantages in comparison with direct application of biogas near



19.1 Advantages of biomethane. Upgrading of biogas to biomethane and feed-in to the gas grid instead of on-site application (1). allows biomethane to be transported and applied more efficiently (2). Furthermore, quantities can be split, traded and transported to various types of applications (3). Using the natural gas infrastructure enables storage, cross-border trade and power generation on demand (4).

the production facility (see Fig. 19.1). Biomethane can be transported through the gas grid to locations where it can be applied more efficiently (stage. 2 in Fig. 19.1), for example in a combined heat and power (CHP) plant operating near a heat sink without the restraint of having to be near the production facility. The dimensions of CHP plants can now be designed to fit the demand (i.e. the heat sink), instead of the size of the anaerobic digestion facility. After feed-in, biomethane is open to new fields of application and gains additional flexibility (stage. 3 in Fig. 19.1). Gas quantities produced on one production site can be used in diverse applications, including

- power generation (e.g. in a CHP) plant
- heating (of buildings or in industry applications)
- as motor fuel in natural gas vehicles (NGVs).

Even non-energy application of biomethane as a raw material for the chemical industry substituting fossil methane is possible. The whole natural gas infrastructure is available to biomethane after feed-in (stage 4 in Fig. 19.1). Just like natural gas, biomethane can be stored and transported, even across borders. Demand-responsive production of power from biomethane

is possible – this can help balancing other fluctuating renewable power sources. The choice of potential substrates for biomethane is, of course, just as versatile as that for biogas and ranges from organic residues to energy plants. All these possibilities turn biomethane into the ‘joker’ in the renewable energy game.

From a political perspective, there are further unique selling points for biomethane. Independence from energy imports increases with the substitution of natural gas for ‘home-grown’ biomethane. At present, biomethane cannot substitute a nation’s supply of natural gas during interruptions to imports in a cold winter month. However, an increased share of biomethane from within its own borders makes a nation’s natural gas supply more reliable. Additionally, the generation of biomethane is economically attractive to the producing country in terms of reducing the costs of importing fuel and increasing employment in the production chain. Rural areas especially profit from biomethane production because a considerable part of the revenue along the value chain is generated there.

Biomethane can be sold as green gas products to consumers, or can be applied according to government support schemes. Legislation in the EU overall and the respective European countries increasingly includes biomethane in support schemes. In many countries, upgrading and feed-in to the gas grid is a well-established practice and government support schemes have triggered market development. These countries include the Netherlands, Germany, the UK, Sweden, Switzerland and Austria. Others, like Hungary and Italy, are developing their first facilities at the time of writing (see Section 19.2). Transport through the gas grid needs to be accompanied by corresponding certification and mass balancing systems (see Section 19.3). One example of such a mass balancing system is the German Biogasregister Deutschland, as outlined in Section 19.4.

19.2 Market development

Biomethane was first mentioned in European legislation (as ‘biogas’) in directive 2003/55/EC. This directive declared a common European market for natural gas, with biomethane as an equal player. This directive was repealed in the meantime by directive 2009/73/EC. In both directives, access to the gas grid, free of discrimination, is granted to biomethane. Although daily business in the case of natural gas, no major European market for biomethane with cross-border trade has developed so far. Different realities in Member States have slowed down the development of a European market for biomethane. A lack of European gas grid technical standards poses barriers for transport between countries. International legislation with differences and incompatibilities regarding grid ownership, national support schemes, auditing and certification complicate international cooperation

and trade. One major barrier for a European market for biomethane lies in the diversity of national countries' support schemes. Another barrier for international trade is caused by limitation of support schemes to domestic production. For example, the German Renewable Energy Sources Act (Erneuerbare Energien Gesetz (EEG)) regulates explicitly that only biomethane that has been fed in within Germany is eligible for support.

The main market drivers for biomethane in European countries are subsidies such as feed-in tariffs (usually for CHP or heat applications) or quota regulations (most commonly used for biofuels). Green gas products addressing eco-sensitive private households or industry players are becoming more and more established all over Europe.

A rising natural gas price might also be a possible future driver. So far though, biomethane is not competitive with natural gas. In Germany, production costs for biomethane are roughly double those of fossil natural gas. The German Federal Network Agency reports average production costs of biomethane of 6.2 cents/kWh (BNetzA, 2011).

Many European countries have set more or less explicit targets for biomethane as part of their overall targets for reaching 20% renewable energy in the total energy mix by 2020. Germany has announced explicit targets for biomethane feed-in in the law regulating access to the German natural gas grid, 'Gasnetzzugangsverordnung' (GasNZV). This law also enables access to the gas grid for biomethane production facilities. The target mentioned here is to replace 6% of national gas consumption by the year 2020 and 10% by 2030. The numbers were defined in absolute energy values to be independent from the nation's natural gas consumption. The target was therefore set to 6 billion Nm³ per year (about 60 TWh/y) by 2020, and 10 billion Nm³ per year (about 100 TWh/y) by 2030. Of the 2020 goal, only 4.5% had been achieved at the end of 2010 (BNetzA, 2011). It seems fairly impossible to be reached at the time of writing – however, it has never been officially revoked. According to the GasNZV, the costs for setting up feed-in facilities have to be paid mostly by the grid operator; part of the costs can be allocated to all German gas grid operators. The goals of some other EU countries are as follows.

- The Netherlands has formulated a target for biomethane feed-in of 202 ktoe (2.3 TWh/y) for 2015 and 582 ktoe (6.8 TWh/y) for 2020 in their National Renewable Energy Action Plan (NREAP). The Netherlands is the only country mentioning a target for biomethane feed-in in their NREAP (Beurskens *et al.*, 2011).
- France is able to replace 2% of the natural gas circulating inside the French gas grid by biomethane by 2020 according to an estimation of a biomethane project manager from GrDF (Gaz réseau distribution France, the French natural gas grid operator). This corresponds to 2.8

to 8.7 TWh/year by 2020. Law updates from 2011 established feed-in support schemes for feed-in of biomethane into the gas grid and for the feed-in of bio-power (ACTU, 2010).

- Austria has no official national target yet. However, the ministries of economy and environment have agreed on a target of 200,000 cars using natural gas with at least 20% biogas by 2020. A strategy for biogas and biomethane is being worked out at the time of writing. The Austrian focus is on transportation. However, a new support scheme comes into effect in 2012, with focus on power and with explicit regulations about biomethane feed-in (BMWFJ & Lebensministerium, 2010).
- The UK's NREAP aims to replace 15% of fossil fuels by 2020 (DECC, 2010). Biomethane is explicitly mentioned as a substitute here, as well as in the government's renewable energy strategy (DECC, 2009) – in both cases without further quantification. The UK government has proposed injection at 7 TWh/y by 2015 (about 1.5% of the domestic gas customer market). Hopes are raised by the recently established renewable heat incentive, defines which support for renewable heat production and biomethane is mentioned as a key supported technology (DECC, 2011). The support pattern is comparable to the German EEG with a fixed price of 6.5 pence/kWh (about 8 cents/kWh) for a period of 20 years. Therefore, it has been stated that the UK biomethane market is about to make the breakthrough (DECC, 2009, 2010, 2011; Mahnke, 2012).

The feedstock applied also differs from country to country. While German biomethane production is dominated by energy crops, the UK focuses on organic wastes. Pioneers of European biomethane upgrade and feed-in are the Netherlands, where plants have been operating since the late 1980s. Sweden operated the highest number of upgrading plants in Europe until 2011, when it was overtaken by the rapid expansion in Germany. As the Swedish gas grid only covers parts of the country, distribution is often achieved by road transport. Of 47 upgrading plants in total, only 8 actually do feed-in. Biomethane is predominately applied as a vehicle fuel in Sweden (dena, 2011).

Table 19.1 presents details on feed-in plants and capacities, market drivers and dominating feedstocks in European countries. Figure 19.2 illustrates feed-in capacity.

In contrast to the national differences already mentioned, consistent European legislation can be referred to in the application of biomethane as vehicle fuel. Directive 2009/28/EC defines targets for renewable energy supply in transport (RES-T) that have to be fulfilled by all Member States. Biomethane may be used as a renewable transport fuel in NGVs and thus help to allow compliance with the RES-T targets. Due to this European regulation, a European standard and, in theory, a European market for

Table 19.1 Production of biomethane in European countries

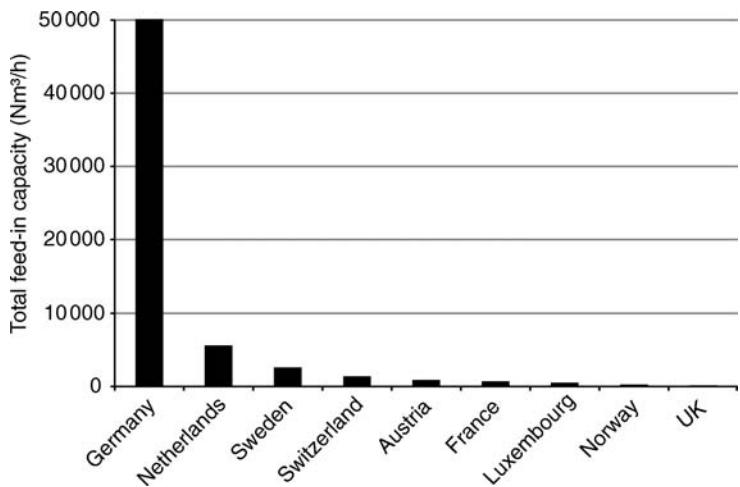
	Number of feed-in plants (+ new in 2011)	Total feed-in capacity (+ new in 2011)	Main market drivers	Dominating feedstock
Germany	80 (+30)	50720 Nm ³ /h (+16110 Nm ³ /h)	<ul style="list-style-type: none"> • Government support schemes for energy crops and CHP 	<ul style="list-style-type: none"> • Energy crops • Organic waste • Manure
Netherlands	13 (+4)	5625 Nm ³ /h (+1980 Nm ³ /h)	<ul style="list-style-type: none"> • Green gas products • Government support schemes 	<ul style="list-style-type: none"> • Organic waste • Sewage sludge • Landfill gas extraction
Switzerland	12 (+1)	1384 Nm ³ /h (+280 Nm ³ /h)	<ul style="list-style-type: none"> • Government support schemes 	<ul style="list-style-type: none"> • Sewage sludge • Manure • Organic waste
Austria	7 (+2)	891 Nm ³ /h (+240 Nm ³ /h)	<ul style="list-style-type: none"> • Vehicle fuels • Government support schemes 	<ul style="list-style-type: none"> • Energy crops • Organic waste • Manure
Sweden	7	2610 Nm ³ /h	<ul style="list-style-type: none"> • Vehicle fuels 	<ul style="list-style-type: none"> • Sewage sludge • Organic waste
Luxembourg	2 (+1)	530 Nm ³ /h (+180 Nm ³ /h)	<ul style="list-style-type: none"> • Government support schemes 	<ul style="list-style-type: none"> • Organic waste • Energy crops
France	2	715 Nm ³ /h	<ul style="list-style-type: none"> • Government support schemes 	<ul style="list-style-type: none"> • Organic waste • Sewage sludge
UK	2	160 Nm ³ /h	<ul style="list-style-type: none"> • Vehicle fuels • Heat market 	<ul style="list-style-type: none"> • Organic waste • Sewage
Norway	1	270 Nm ³ /h		

Source: Unpublished data from the dena project 'biogaspartner'.

biomethane exist in this sector. Bilateral cross-border transactions have already taken place: transactions from Germany to the Netherlands and from Germany to Sweden have been successfully completed. However, a larger market, with standardized or even liquid biomethane assets has not yet developed.

19.2.1 Case study: biomethane feed-in in Germany

Germany is by far Europe's largest market for biomethane (see Fig. 19.2). Germany's elaborate legislation regarding biomethane support addresses all the main markets by suitable support schemes. The biomethane producer

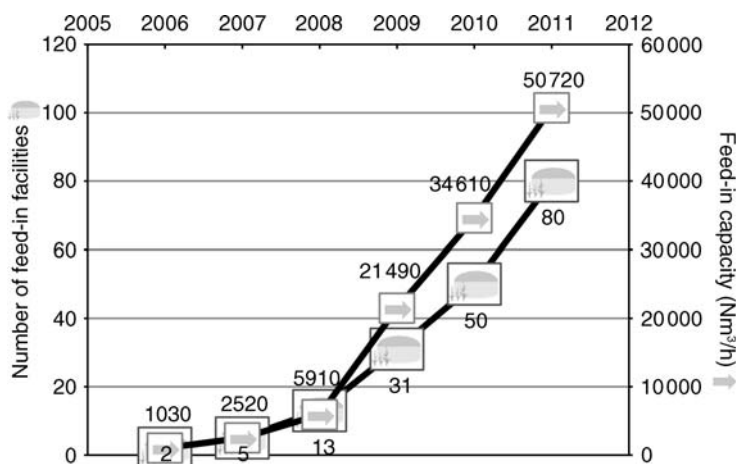


19.2 Feed-in capacities in Europe.

can choose between power generation (via the Renewable Energy Sources Act, EEG), heating (Renewable Energy Heat Act, EEWärmeG), motor fuels (European Bio-fuels Quota Act) and, of course, the green gas product market. The latter, however, is not subject to any governmental support mechanism. The EEG is designed for specific development of the markets. Smaller plants are supported with higher prices in order to support the development of decentralized power generation. In contrast to some other European countries, energy crops are explicitly supported in order to establish a national source of biomethane.

The first feed-in plants started operation in 2006 (in Pliening, Bavaria and Straelen, North Rhine–Westphalia), aiming for the support defined in the EEG which became effective in 2004. Soon after this, a dynamic development started that led to a total number of about 80 plants operating at the end of 2011 (see Fig. 19.3). However, the low price for natural gas undermined the support by biomethane feed-in tariffs for electricity in new CHP plants around 2010. As a result, the sale of biomethane became more and more difficult and the strong growth in the creation of new projects decelerated dramatically. This decline is expected to become apparent after 2012, when projects initiated before 2010 are completed. The vehicle fuel market is developing slowly at the time of writing this chapter, limited by the number of NGVs and biogas station infrastructure. Only a few large production facilities are dominating this market.

Since 2010, the EEWärmeG regulated the need to provide a regenerative heating concept for new houses, which can also be fulfilled by heating with biomethane. The possibility of supplying a larger part of already existing



19.3 Development of biomethane gas grid feed-in in Germany between 2006 and 2011 showing strong growth in later years. Comparison of the number of facilities with the total capacity of gas grid feed-in shows a trend to larger facilities over the years (Source: unpublished data from the dena project 'biogaspartner').

buildings with heat from biomethane is not covered – it is still considered a sleeping giant by the biomethane industry.

Green gas products are still a niche market. However, they are developing – driven by rising environmental awareness and also by the above-mentioned obligations for renewable heating of new buildings.

A *defacto* end of the 'book and claim' trading of biomethane certificates was the result of the 2011 EEG update (for a definition of book and claim see Section 19.3). The use of book and claim certificates is no longer applicable for Germany's national support schemes. This hit many market participants very hard as they had transferred large parts of their unsold quantities into valid certificates of this type in the hope of selling them in later years when demand improved. For the (relatively small) green gas product market, this path can still be chosen.

19.3 Biomethane certification and mass balancing

As a means of direct promotion of biomethane feed-in by government support schemes, two important general approaches can be observed – feed-in tariffs and quota obligations. Indirect promotion for biomethane is achieved by other means, such as tax refunds or financial support for new projects.

Laws establishing a feed-in tariff pattern define a guaranteed price for the feed-in of renewable energies into the public (power) grid for a long period

of time, usually 10–20 years. This combination enables predictable long-term planning for private investors and therefore can trigger huge investments without further public funds. The costs for payment of the (higher) price are spread among all energy consumers; this is administered by grid operators. Thus, government involvement in the process is kept at a minimum level. The legislative authority can tailor support schemes of this type to explicitly set the focus of promotion. The role model for minimum pricing support schemes is the German EEG, a law for the promotion of renewable energies in the electric power grid. Similar laws for the promotion of renewable energies have been implemented in more than 60 countries worldwide in a similar form (BMU, 2011; REN21, 2011). Regarding power from biomass, the German EEG explicitly supports smaller production facilities, the use of certain types of feedstock (energy crops, slurry, organic waste) and, of course, upgrading and feed-in of biomethane.

In contrast, quota obligations (or ‘renewable portfolio standards’) define a minimum quota to be fulfilled by renewable energies (here, biomethane). The most famous example of quota obligations is the Biofuels Quota Act issued by the EU, which has been implemented in Member States. Another example is the German EEWärmeG. Quota obligations promote the most cost-effective technology. Feed-in tariff schemes can be very effective in promoting a market and developing technologies on a broad level. Both approaches (feed-in tariffs and quota obligations) have their pros and cons, qualifying them to coexist (REN21, 2011).

The European motor fuel quota obligation from directive 2009/28/EC defines a European certification standard: biomethane can be used in NGVs as biofuel. For this, biomethane needs to comply with the sustainability criteria of the directive (which includes greenhouse gas (GHG) reductions of 60% for facilities built post-2018 as compared to the displaced fossil fuel on a whole cycle life basis). The law was actually designed for liquid fuels; for the particular case of biomethane, questions remained open. The specified mass balancing method was defined for transporting sustainable fuels inside ships or trucks with clear boundaries. In the case of transport through the gas grid, these boundaries could not be easily defined. The view seems to have become accepted, that the whole gas grid is regarded as the ‘tanker’. With this approach, application of biomethane is also possible as international trade, as noted earlier.

In contrast to this EU directive, other government support schemes in Europe vary significantly. These variations occur due to different infrastructure and raw material bases as well as diverse political frameworks and goals. For example, as already mentioned, the Netherlands have established a well-developed heat market for eco-friendly green gas. Germany, Austria and Slovakia have established feed-in tariffs for

Table 19.2 Overview of biomethane transport mechanisms regarding mode of transport, separation of gas types and back tracing

Physical identity	Mass balancing	'Book and claim', trading certificates
<ul style="list-style-type: none"> • Biomethane transport inside closed vessel, e.g. tank truck or separated grid • No mixing with other gas types allowed, not even with other biomethane types • The originally produced molecules are applied 	<ul style="list-style-type: none"> • Transport e.g. inside natural gas grid • Mixing of biomethane with natural gas or other biomethane types is possible • Back tracing from source to application is possible 	<ul style="list-style-type: none"> • No physical transport necessary • Separation of commodity (natural gas) and 'biogas properties' both have tradable value • No back trace possible

electricity from biomethane in CHP plants. Upgrade and feed-in is supported by special bonuses in these countries.

Three options for regulating transport and balancing mechanisms are presented in Table 19.2. If physical identity is required to be preserved, transport needs to be done in a way that prevents mixing with other types of gas, even with other types of biomethane, for example from different feedstock (see Table 19.2). Therefore only delivery within closed vessels (e.g. inside a special tanker or a separate grid) is applicable. At the moment of feed-in into the public grid, physical identity can no longer be provided.

A mass balancing system is reasonable, if mixing with other (fossil) commodities is allowed, but the path from application back to the source needs to be traceable (see Table 19.2). In this way, conventional means of transport can be used as long as mass balancing is operated in parallel as well. Mass balancing is defined in the EU directives 2009/28/EC and 2009/30/EC.

A certificate system ('book and claim') makes sense if only promotion of the special (green) product is desired and the transport chain to the customer can be neglected (see Table 19.2). In this case, the green properties are separated from the gas, which is then treated as natural gas. The green properties are traded separately, and tracing back to source is usually impossible. On application, the certificate is recombined with natural gas and afterwards regarded as biomethane again. The guarantee of origin system is (vaguely) defined in directives 2001/77/EC (repealed) and 2004/8/EC for the European electricity market: the corresponding certificate, for example, guarantees the renewable origin of a certain amount of (electric) energy.

The book and claim option is the more simple and more flexible. It is

Table 19.3 Selected tracking schemes for biomethane in Europe

Country, name of tracking scheme	Initiation and operation	Website
Germany: Biogasregister Deutschland	<ul style="list-style-type: none"> • Initiated by the German Energy Agency (dena) and 14 companies from the biomethane market • Operated by dena • Since 2011 	www.biogasregister.de
Netherlands: Vertogas	<ul style="list-style-type: none"> • Initiated by gas grid operator Gasunie • Operated by Vertogas • Since 2009 	www.vertogas.nl
UK: Green Gas Certification Scheme	<ul style="list-style-type: none"> • Initiated by Renewable Energy Association (REA) and founding partners • Since 2011 	www.greengas.org.uk

therefore preferred by trading parties: they do not need to organize any gas transport and they can trade the certificates as a separate commodity.

The vision for biomethane to be an equal player and to replace natural gas in significant amounts in the gas grid strengthens the need to apply mass balancing systems for transport. With increasing biomethane feed-in, the gas grid needs to be more and more decentralized. It is then no longer acceptable that biomethane producers do not bear their share of the costs in this conversion process: book and claim mechanisms would allow them to do so because transport balancing is avoided. Therefore, in the case of biomethane, the use of mass balancing systems might become the future path.

19.4 European mass balancing schemes for biomethane

A few mass balancing certification schemes have evolved in Europe, as shown in Table 19.3. In Switzerland, labelling has been carried out in the 'naturemade' scheme since 2009 and Denmark has used its 'Energi-net' scheme since December 2011. These schemes do not follow any common standard because they are tailored to fit each nation's situation. Austria's mass balancing system is scheduled to start operation in mid 2012.

A mass balancing system keeps track of the amounts of biomethane transported from production to final application. Any trading or splitting of amounts is tracked and accompanied by a corresponding transaction inside the system. Double marketing of amounts inside the mass balancing system is impossible due to precise amount registration. It is possible to trace back to source any biomethane amount inside the mass balancing system, making

it possible to deliver further proof in case of doubt, even after discharge from the gas grid.

In order to further enable trade and promotion of biomethane inside the natural gas grid, a combination of mass balancing and quality certification is needed. Quality requirements define the type of registered biomethane quantities. Such quality requirements may be specified related to substrate input, facility sizes, sustainability criteria and many more, depending on the demands of the market. On the base of this, trading parties can define biomethane deliveries inside the gas grid. German governmental support schemes define more than 50 different biomethane products and sub-products, all aiming at different tariffs, bonuses, tax refunds or quota fulfillments (dena, 2012a).

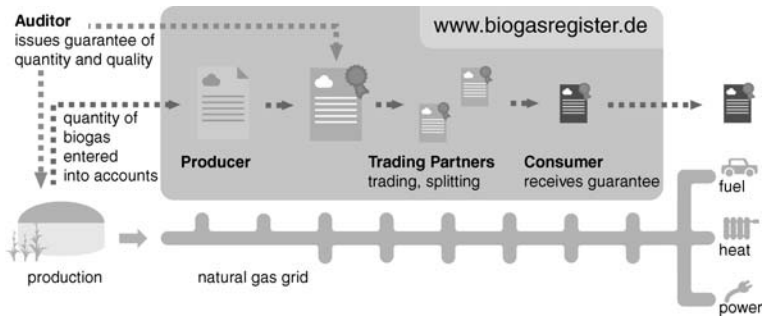
When defining quality requirements, it is important to consider that, at the moment of feed-in (and mass balancing registration), the decision about the final application of the biomethane is still potentially open. Vendors in the trade chain may decide differently about the market or the desired support scheme for biomethane amounts of the same origin. Therefore, amounts cannot be classified by their final application (e.g. CHP gas, vehicle fuel, etc.) at the moment of feed-in.

In order to avoid fraudulent or inaccurate claims, independent auditors certify the amounts and quality of registered amounts and report to the mass balancing system. Corrections to meter readings need to be made, for example if fossil propane is added to biomethane for adjustment of calorific value.

If an amount is removed from the mass balancing system, the resulting certificate should contain information about the final application. Thus, the individual certificate can only be applied for this special purpose (e.g. power generation support scheme, fuel quota, heating) – otherwise, multiple applications of the certificate are still possible.

19.4.1 Case study: the German biogas register (Biogasregister Deutschland)

The German biogas register ‘Biogasregister Deutschland’ was established by the German Energy Agency (dena) and 14 companies from the biomethane industry. It started operation in 2011 and has become an important element of verification management, as a complement to gas balancing within the grid and trading steps in the market. The register was financed and designed without any direct involvement of the government or state – however, the responsible federal ministry for the environment (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit) accompanied parts of the process with advice and recommendations.



19.4 Mass balancing according to Biogasregister Deutschland's mode of operation. Parallel to the transport of biomethane through the natural gas grid from production to application, Biogasregister Deutschland offers documentation of quality and quantity. Independent auditors validate all entries. The final account statement (Biogasregister-Auszug) documents application of biomethane.

The basic idea behind Biogasregister Deutschland was to provide a general biomethane standard for the German market. German support legislation regarding biomethane defines, in a detailed manner, what needs to be proven but not how it needs to be proven. More than 800 power grid operating companies have to decide over distribution of EEG support in Germany and a common standard was thus needed to help market development. The standard has been defined by a few dozen criteria (dena, 2012b) covering all German support schemes, for example for substrate types, production facility size or for other facts that need to be proven in order to gain the different support possibilities in German legislation. With these criteria, summarized evidence for registered amounts is collected. The documentation is based on neutral authorized experts who lodge quality and quantity reports in the database. The German Biogas register thus links the task of a mass balancing system directly with documentation of biogas quality.

Another main idea behind the biogas register was to create a basis for flexible biomethane assets in the German market. Once the register has gained confidence in the market, market participants can rely on its standards and documentation and then do not need to rely only on trust between trading partners – a quantity documented within the Biogasregister Deutschland can be accepted with confidence without further checking. The possibility for fraudulent double marketing is negated for those who use the register because biomethane amounts can only be introduced with the check of an independent auditor.

Figure 19.4 shows the mode of operation of Biogasregister Deutschland. It keeps the following principles for all entries.

- The producer enters information about a biomethane amount or production facility.
- An independent auditor checks and validates the producer's statements and hands in the expert report as proof.
- A formal check is conducted by the biogas register to ensure proper functioning.

As a first step, the producer enters the produced amounts or a new production facility into his own accounts. The amounts are then in an incomplete status (grey) as neutral checking has not yet taken place. Nevertheless, the amounts entered can be split and transferred to the accounts of the producer's trading partners and customers. A neutral auditor then checks production and facilities according to the list of criteria issued by the Biogasregister Deutschland (dena, 2012b). The auditor issues a guarantee of origin, quality and quantity and enters it in the Biogas register. Amounts with activated criteria change to full status (green) inside the register and can now be removed from the register. Final consumption of the biogas is documented by generation of a final biogas account statement, the Biogasregister-Auszug. In this step, the 'green' amount is inactivated (status switches to red) and it cannot be split or transferred any further.

The account statement lists all relevant information regarding quantities, origin, activated criteria and the points of entry and exit of the gas grid. Declaration of the intended purpose makes double accounting on parallel applications impossible (e.g. motor fuel and CHP). The recipient can tell by the documented criteria which markets can be addressed with this biogas amount and which special support bonuses can be claimed.

The German biogas register's catalogue of criteria is designed to be extensible; this enables flexible adaption to new national laws or for inclusion of other countries support standards. At the time of writing (2012), the list of criteria was extended for the first time due to a change in German biogas support laws. On the way to international markets, the criteria of new countries need to be distilled from the countries support schemes or market needs, and then added to the list. After incorporating these new criteria into the register, the new market can also be addressed.

The Dutch Vertogas scheme was established in 2009 by the public Dutch gas grid operator company Nederlandse Gasunie NV. Plans exist to make use of Vertogas compulsory to biomethane support schemes under public law.

Vertogas' mode of operation is similar to that of Biogasregister Deutschland. A first audit is needed to completely register the facility before enabling accounting of amounts. All registered amounts are checked by neutral auditors. The transfer of amounts between trading parties is done

without involvement or checking of the operator, but back-tracing is possible. After application, the specific amount is depleted and cannot be used further.

The schemes differ in some respects. In Vertogas, auditing of production facilities and biomethane amounts takes place on a monthly basis; the German biogas register does not specify any interval. Biogasregister Deutschland's amounts are entered manually into the accounts, whereas Vertogas transfers feed in meter readings automatically to the database. The smallest unit in Vertogas is 1 MWh (about 100 Nm³ of gas equivalent); Germany's Biogas register's smallest unit is 1 kWh.

19.5 Future trends

Biomethane will be an important piece of the puzzle during the conversion of our energy system to renewable sources. Production of power on demand from biomethane directly connects the gas grid and the power grid – the gas grid can help to balance the power grid. The gas grid may change its face from distribution of fossil gases to being the energy balancing service provider with short-term and seasonal storage options.

Increasing integration of decentralized biomethane feed-in into the gas grid is a new situation for the gas grid infrastructure with new challenges. New gas sources and therefore new paths of transportation may make grid adaptations at all pressure levels necessary, starting with the distribution grid. There are examples in Germany of facilities feeding in more biomethane to the local distribution network than is discharged in total; the excess gas is compressed and transferred to a higher level.

With increasing biomethane production from energy crops, its impact on agriculture will come into sharper focus. The obligation of applying sustainability criteria to biomethane production may be expected in the near future. The case of biomethane can make some favorable contribution to the discussion: by application of digestion residues as fertilizers near the production site, local nutrient cycles can be closed. Additionally, energy-intensive production of nitrogen fertilizers and exploitation of declining global phosphorous reserves can be avoided. Further utilization of biomass waste potential may also close loops in the recycling economy and is probably a trend in the coming years.

Biomethane is the most efficient biofuel with regard to fuel production equivalent per area of crop land. Biomethane is expected to play a bigger role in the fuel market due to government support, increasing application in NGVs and with regard to GHG emissions (FNR, 2009).

Slowly increasing awareness of biomethane is evident in the legislation of European countries. The perception is shifting from being regarded as a sub-branch of biomass production to being an independent renewable energy

product with special features and advantages. Increasingly, laws and strategies are including biomethane. Awareness of biomethane as an attractive renewable energy source is steadily rising, thanks in some part to its inclusion in NREAPs. However, as of 2012, biomethane is still not considered in the selection of available renewable technologies in many countries.

In the long term, a European strategy for biomethane could be designed to boost production. This strategy could focus on standardized production conditions (sustainability, agriculture), deliver an approach to international exchange of biomethane or establish a framework to pan-European power grid balancing.

Guiding biomethane production from dependency on government support schemes to market competition with fossil natural gas may be another future challenge. A rising price for natural gas will accelerate this process. On a European level, the European cap-and-trade for GHGs may also be a future driving factor: application of biomethane omits GHG emissions, therefore no compensation with GHG certificates is necessary. However, it may take some time before either the price for natural gas or for certificates bridges the gap.

European biomethane markets are going to emerge over the coming years in line with expansion of biomethane feed-in. The growth rate of the German market is expected to slow down, but strong growth is expected in other countries, for example the UK. International markets may evolve in the next few years if barriers to the transfer of biomethane between countries can be removed. Until such transfer can be done freely, non-transparent regulations, different standards and administrative barriers need to be overcome. This issue is addressed, for example, by the GreenGasGrids project (www.greengasgrids.eu; Strauch and Krassowski, 2012). Evolving markets will create their own demand and supply, and exchange between the countries will be favorable. The green gas product market is also open to international trade. The establishment of the biofuels quota has created a first European market on this field. Legislation regarding sustainability criteria is an example for European certification standards.

Different countries have created their own set of support schemes that are focused on individual situations and are designed with respect to the countries' priorities. Countries could open their support schemes to imported biomethane from neighboring countries so that international trade can develop. However, support schemes are usually intended to implement a national source of energy and are therefore unlikely to be opened for exchange.

International trade of biomethane should be based on exchange of biomethane amounts between mass balancing systems. Broadly accepted mass balancing systems can facilitate customs clearance by transparent

documentation of the renewable quality of biomethane crossing the border inside the gas grid. Once a European (or at least bilateral) standard for tracking cross-border trade is established, customs authorities will be able to accept this as usual procedure. An increasing need for bilateral trade through existing mass balancing schemes is apparent from inside and outside the German market and also in the requests to Biogasregister Deutschland. The challenge will be the architecture of the international mass balancing standard and one question that needs to be answered is whether it is favorable to create a pan-European register or whether it is more efficient to start with bilateral exchange between equal national registers. Straightening of differences in different nations' situations is another important issue to be solved in the course of internationalization. The standard must be open to new countries' markets with their own evolving framework. Harmonization of more individual mass balancing systems might become more complex and will call for a general European regulation.

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Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC

German legislation available at: www.gesetze-im-internet.de

EEG (Gesetz für den Vorrang Erneuerbarer Energien, also Erneuerbare-Energien-Gesetz)

GasNZV (Verordnung über den Zugang zu Gasversorgungsnetzen, also Gasnetzzugangsverordnung)

EEWärmeG (Gesetz zur Förderung Erneuerbarer Energien im Wärmebereich)

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