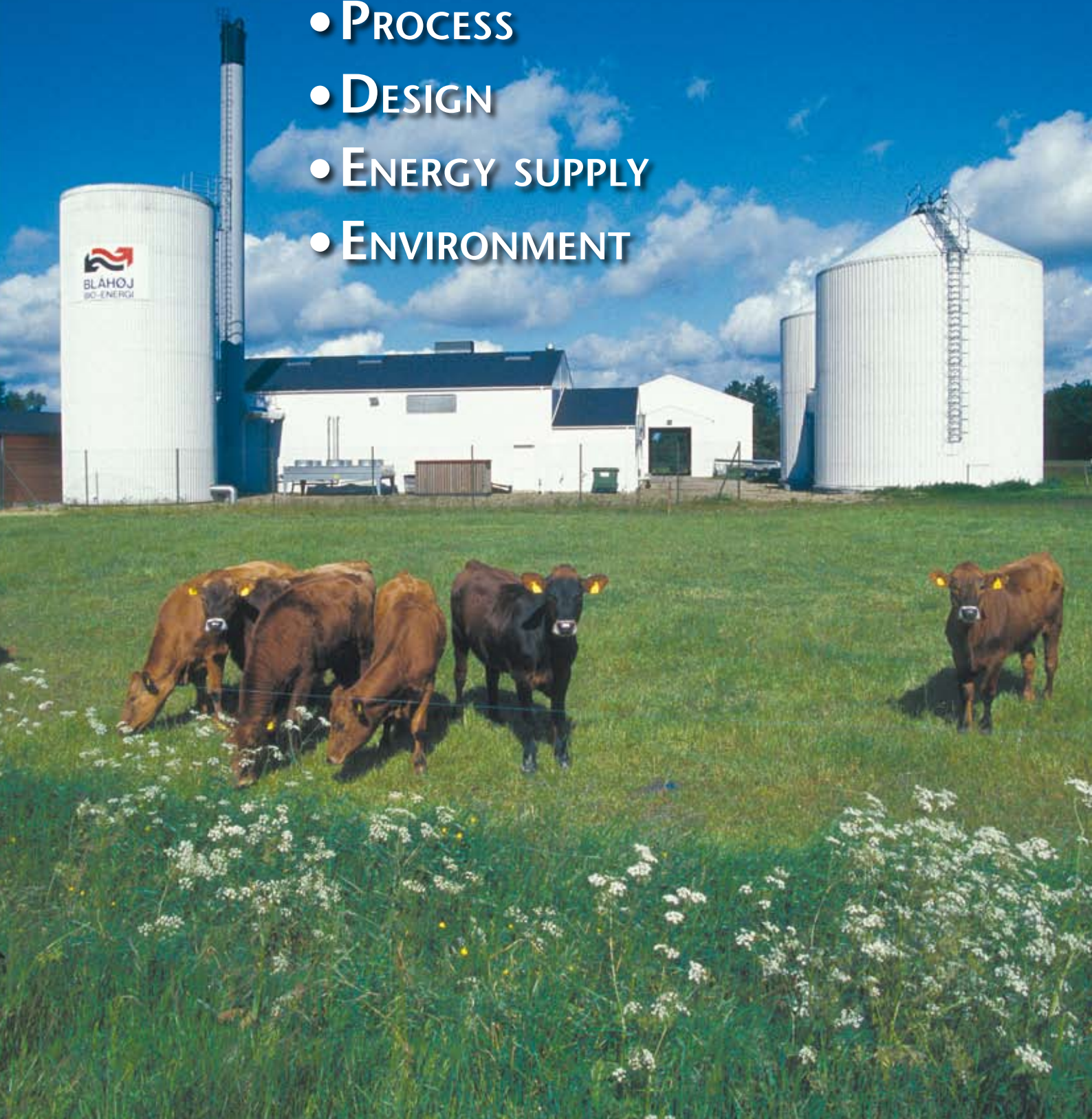Peter Jacob Jørgensen, PlanEnergi

# BIOGAS
## – GREEN ENERGY

- **PROCESS**
- **DESIGN**
- **ENERGY SUPPLY**
- **ENVIRONMENT**

# CONTENTS

# WHAT IS BIOGAS?

*Biogas should burn as cleanly as possible.*

Biogas is a combustible mixture of gases (see figure 1). It consists mainly of methane ($CH_4$) and carbon dioxide ($CO_2$) and is formed from the anaerobic bacterial decomposition of organic compounds, i.e. without oxygen. The gases formed are the waste products of the respiration of these decomposer microorganisms and the composition of the gases depends on the substance that is being decomposed. If the material consists of mainly carbohydrates, such as glucose and other simple sugars and high-molecular compounds (polymers) such as cellulose and hemicellulose, the methane production is low. However, if the fat content is high, the methane production is likewise high.

Methane – and whatever additional hydrogen there may be – makes up the combustible part of biogas. Methane is a colourless and odourless gas with a boiling point of -162°C and it burns with a blue flame. Methane is also the main constituent (77-90%) of natural gas. Chemically, methane belongs to the alkanes and is the simplest possible form of these. At normal temperature and pressure, methane has a density of approximately 0.75 kg/m³. Due to carbon dioxide being somewhat heavier, biogas has a slightly higher density of 1.15 kg/m³. Pure methane has an upper calorific value of 39.8 MJ/m³, which corresponds to 11.06 kWh/m³. If biogas is mixed with 10-20% air, you get explosive air, which – as the name indicates – is explosive!

| Gas | % |
|---|---|
| Methane ($CH_4$) | 55 – 70 |
| Carbon dioxide ($CO_2$) | 30 – 45 |
| Hydrogen sulphide ($H_2S$) | |
| Hydrogen ($H_2$) | 1 – 2 |
| Ammonia ($NH_3$) | |
| Carbon monoxide (CO) | trace |
| Nitrogen ($N_2$) | trace |
| Oxygen ($O_2$) | trace |

*Figure 1. Composition of biogas. The actual make-up depends on what is being decomposed.*

# How is biogas produced?

Biogas is produced naturally in swamps, bogs, rice paddies, etc., (see figure 2) and in the sediment at the bottom of lakes and oceans where anaerobic conditions prevail at a certain depth (see figure 3). Methane is also created in the rumen of ruminant animals (cows, sheep, deer, camels, lamas, etc.).
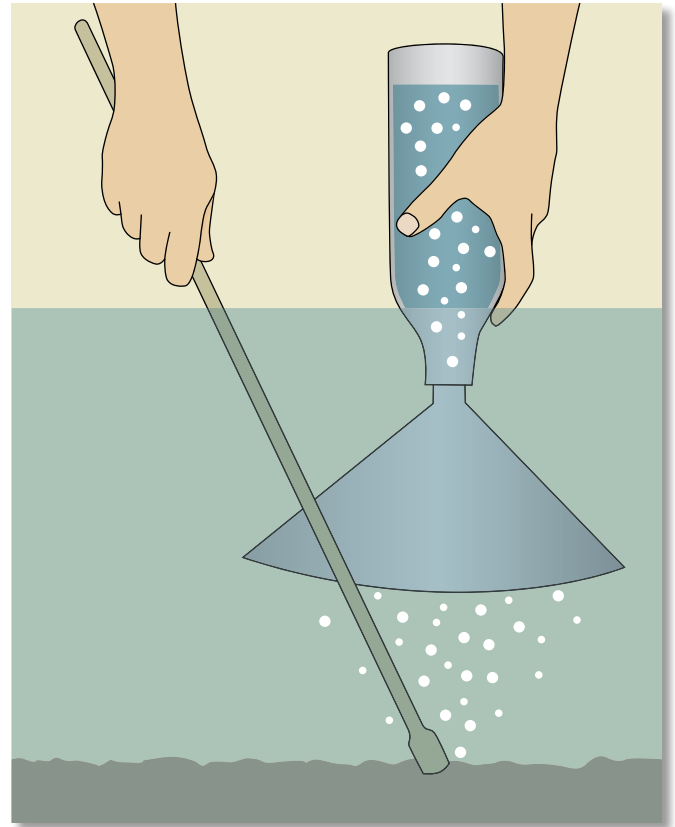


*Figure 2. The biogas formed at the bottom of bogs and other places with naturally anaerobic conditions can be collected in an upturned bottle with a funnel. The bottle should be filled with water from the start so that the rising methane can replace the water without getting mixed with atmospheric air.*
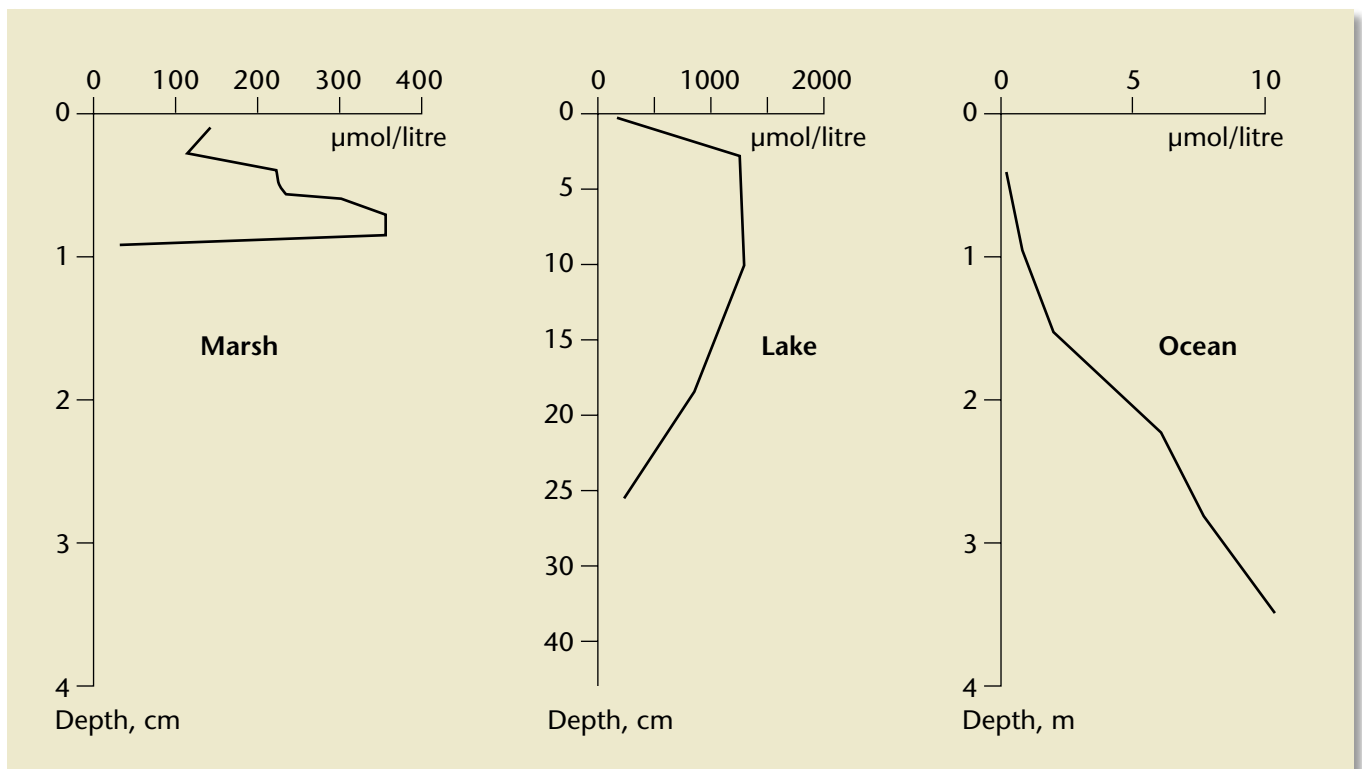


*Figure 3. The methane concentration in sediments (the benthic zone) on the floor of marshes, lakes and oceans. The methane concentration is an expression of the quantity of methane-producing bacteria present.*

### The impact of methane on the climate

Human activities such as cattle farming, rice farming and the accumulation of waste on large waste disposal sites, etc., are thought to have caused a doubling of the atmospheric concentration of methane to the present level of 1.7 ppm. This does not, as such, have any effect on human health. However, as methane is part of the chemical processes in the atmosphere and is also a powerful greenhouse gas (about 22 times as powerful as carbon dioxide, $CO_2$), the gas is a contributor to the greenhouse effect. Methane has thus contributed about 20% to the total increase in the greenhouse effect caused by human activities.

If the greenhouse effect results in an increasing temperature rise on our planet, there is a risk that the large areas of tundra currently under permafrost will slowly thaw, which will result in the release of huge quantities of methane when organic materials are gradually decomposed. This will obviously further exacerbate the greenhouse effect (see figure 4).

Methane in large quantities also destroys ozone. Rising methane emissions can therefore have unfortunate consequences for the ozone layer that helps protect the Earth against the harmful ultraviolet radiation from the sun.

# THE HISTORY OF BIOGAS PRODUCTION

People have known of the existence of naturally produced biogas since the 17th century and experiments with the construction of actual biogas systems and plants started as early as the mid 19th century. One of the oldest biogas systems is the septic tank, which has been used for the treatment of wastewater since the end of the 19th century and is still used for isolated properties where there is no sewerage system. In this type of plant the biogas is, however, not collected and used.

In the 1890s, the Englishman Donald Cameron constructed a special septic tank, from which the gas was collected and used for street lighting. In Denmark the construction of biogas plants for wastewater treatment started in the 1920s. The gas was initially used to heat the plant's digestor tank and the main purpose was therefore not to extract energy, but to decompose organic matter in the wastewater and thus reduce and stabilise the sludge, which is a product of the treatment process.

In the following period and until shortly after the Second World War, there was a substantial growth in the biogas industry, particularly in Germany, Britain and France, and the



*Figure 4. Reindeer in the tundra on Svalbard – both are active producers of methane and thus contribute to the greenhouse effect. The reindeer is a ruminant and produces methane in the rumen and the tundra releases methane during the summer thaw of the frozen ground. With a warmer climate, progressively more methane will be released, which will contribute to the enhanced greenhouse effect, thus increasing global warming. And so a vicious circle has started.*

technology also gradually found its way into agriculture with energy production as the main purpose.

At the end of the 1950s, development nearly stopped, however, due to the cheapness of the fossil fuels oil and gas. The interest in biogas was not reawakened until the mid 1970s following the oil crisis in 1973. The Danish state initiated a research and development programme with the aim of testing and constructing different types of biogas plants using animal manure as the main source of biomass.

Today (2009) there are about 60 biogas facilities installed at sewage treatment plants. In addition, around 20 communal biogas plants of various sizes have been constructed to treat manure, slurry in particular, from a number of livestock farms. These biogas plants also take in large amounts of organic waste from the food industry and slaughterhouses, whereby the energy from the waste is extracted and the nutrients recycled to the agricultural sector. On top of this, there are approximately 60 on-farm facilities and a number of biogas plants associated with landfill sites and with different industries that produce waste water with a high organic content (see figure 5).

From the mid 1990s, the expansion of the biogas sector once again stagnated in Denmark due to lack of economic incentives. But with the political agreement in Folketinget in 2008 on an energy policy promoting green energy and on a better price for electricity produced from biogas, the sector is slowly starting to wake up again.

| | Number | Biogas production in Denmark in 2006 1,000 m³ |
|---|---|---|
| Municipal sewage treatment plants | 61 | ~ 40,000 |
| Communal biogas plants | 19 | ~ 73,000 |
| Farm biogas plants | 57 | ~ 33,000 |
| Landfill gas plants | 25 | ~ 18,000 |
| Industrial plants | 5 | ~ 7,000 |
| Total | 167 | ~ 171,000 |

Total biogas production in Denmark is 4 PJ, which is about 5‰ of the total energy consumption.

Figure 5. Biogas production in Denmark in 2006.

## BIOGAS IN DEVELOPING COUNTRIES

A number of developing countries use biogas extensively. In India and China alone, there are more than one million small, simple plants, each treating waste (sewage, animal manure, crop residues, etc.) from a single household. The plants are dug into the ground and are unheated. The biogas is used in the housekeeping for cooking and the digested biomass is used as a fertiliser (see figure 6).
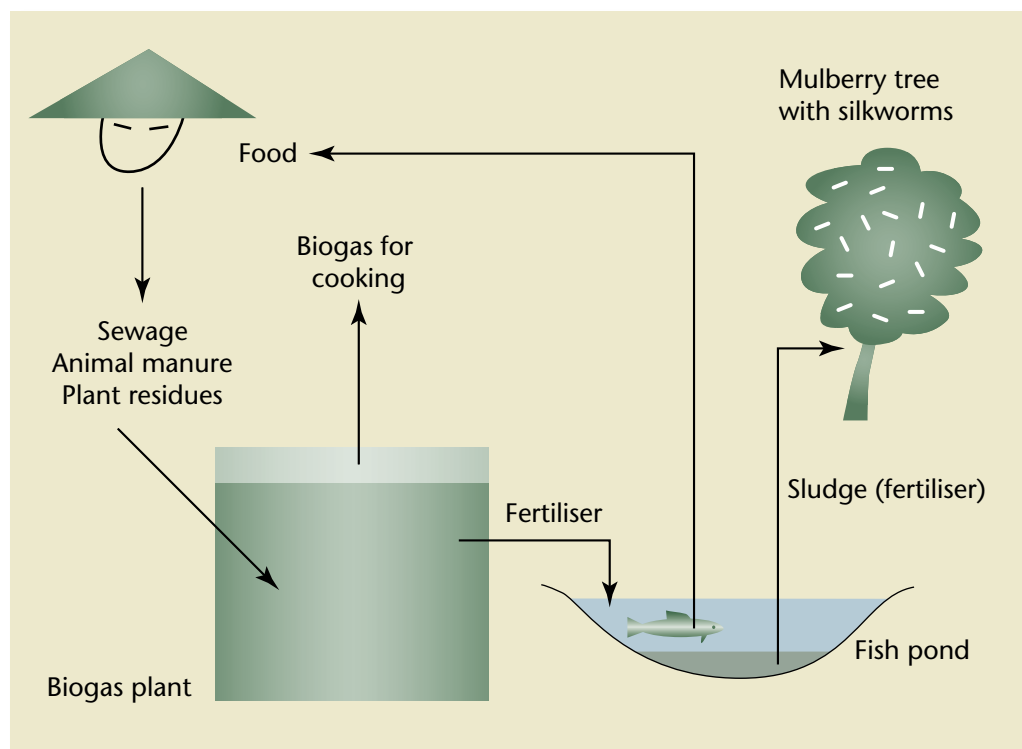


Figure 6. An interesting ecological cycle with biogas as the central unit is practised in many places in China.

7

# THE BIOGAS PROCESS

The complete biological decomposition of organic matter to methane ($CH_4$) and carbon dioxide ($CO_2$) under oxygen-depleted conditions – i.e. anaerobic – is complicated and is an interaction between a number of different bacteria that are each responsible for their part of the task. What may be a waste product from some bacteria could be a substrate (or food) for others, and in this way the bacteria are interdependent.

Compared with the aerobic (oxygen-rich) decomposition of organic matter, the energy yield of the anaerobic process is far smaller. The decomposition of, for example, glucose will under aerobic conditions give a net yield of 38 ATP molecules, while anaerobic decomposition will yield only 2 ATP molecules.

This means that the growth rate of anaerobic bacteria is considerably lower than that of aerobic bacteria and that the production of biomass (in the form of living bacteria) is less per gram decomposed organic matter. Where aerobic decomposition of 1 g substance results in the production of 0.5 g biomass, the yield under anaerobic conditions is only 0.1 g biomass.

The biogas process is often divided into three steps: Hydrolysis, acidogenesis and methanogenesis, where different groups of bacteria are each responsible for a step (see figure 7).
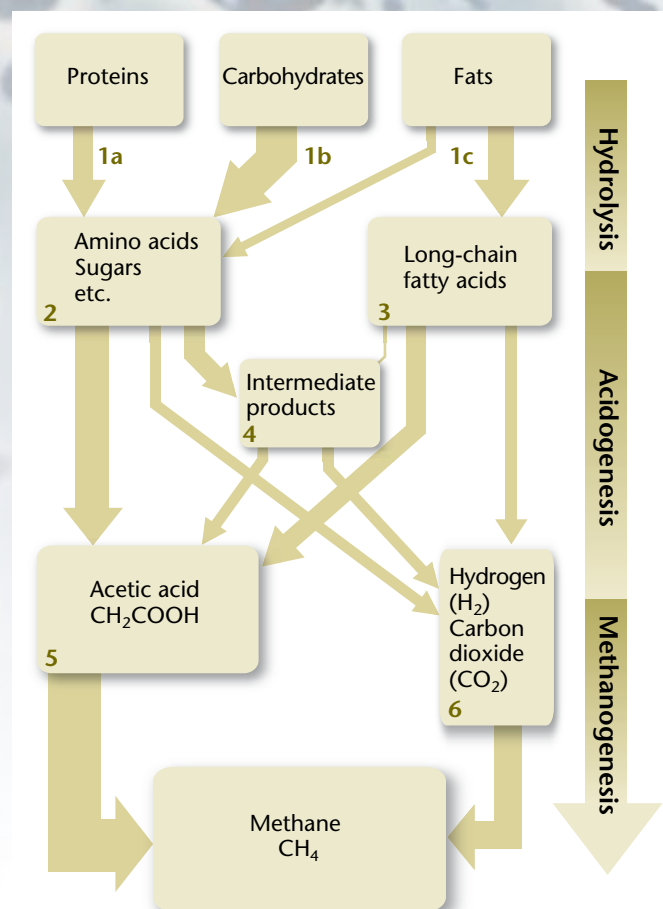
Figure 7. The anaerobic decomposition of organic matter consists of three main phases: A. Hydrolysis (1a, 1b, 1c). B. Acidogenesis, also called fermentation (2, 3, 4). C. Methanogenesis (5, 6).

# HYDROLYSIS

During hydrolysis long-chain molecules, such as protein, carbohydrate and fat polymers, are broken down to monomers (small molecules). Different specialised bacteria produce a number of specific enzymes that catalyse the decomposition, and the process is extracellular – i.e., it takes place outside the bacterial cell in the surrounding liquid.

Proteins, simple sugars and starch hydrolyse easily under anaerobic conditions. Other polymeric carbon compounds somewhat more slowly, while lignin, which is an important plant component, cannot be decomposed under anaerobic conditions at all.

Cellulose – a polymer composed of a number of glucose molecules (see figure 8) – and hemicellulose – composed of a number of other
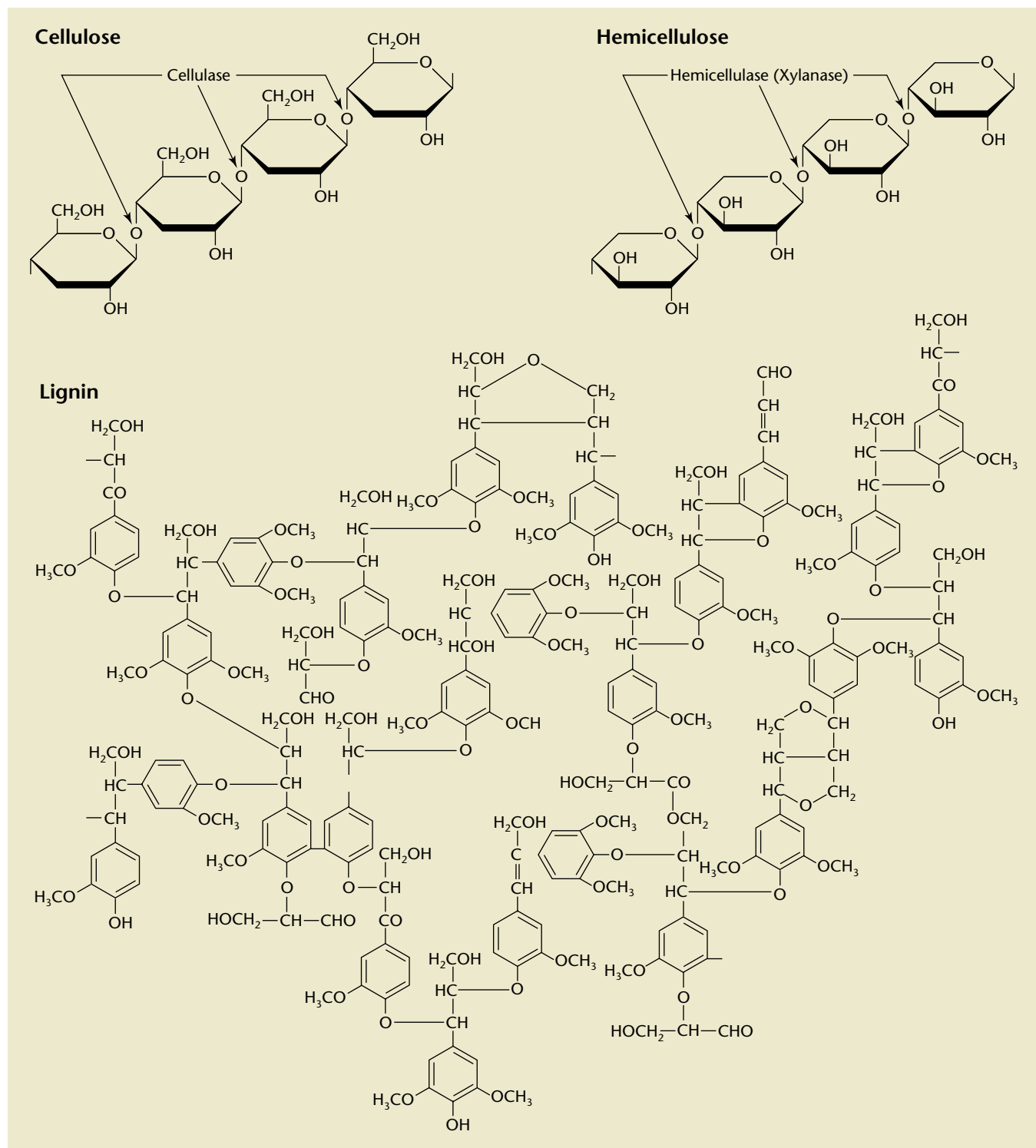


*Figure 8. Cellulose and hemicellulose are long-chain polysaccharides that can be broken down by specific enzymes present in certain bacteria, but not in animals. Lignin has a compact structure and is practically biologically inert.*

sugars – are complex polysaccharides that, are easily hydrolysed by specialised bacteria. In plant tissue both cellulose and hemicellulose are tightly packed in lignin and are therefore difficult for bacteria to get at. This is why only approx. 40% of the cellulose and hemicellulose in pig slurry is decomposed in the biogas process. Normally the decomposition of organic matter to methane and carbon dioxide is not absolute and is frequently only about 30-60% for animal manure and other substrates that have a high concentration of complex molecules.

## FERMENTATION – ACIDOGENESIS

In a balanced bacterial process approximately 50% of the monomers (glucose, xylose, amino acids) and long-chain fatty acids (LCFA) are broken down to acetic acid ($CH_3COOH$). Twenty percent is converted to carbon dioxide ($CO_2$) and hydrogen ($H_2$), while the remaining 30% is broken down into short-chain volatile fatty acids (VFA).

Fatty acids are monocarboxylic acids that are found in fats. Most naturally occurring fatty acids contain an even number of carbon atoms. VFAs have fewer than six carbon atoms. LCFAs have more than six carbon atoms (see figure 9).

If there is an imbalance, the relative level of VFAs will increase with the risk of accumu-

| Monocarboxyl acids | |
| --- | --- |
| **VFA** | |
| Formic acid | HCOOH |
| Acetic acid | $CH_3COOH$ |
| Propionic acid | $C_2H_5COOH$ |
| Butyric acid | $C_3H_7COOH$ |
| | |
| **LCFA** | |
| Lauric acid | $C_{11}H_{23}COOH$ |
| Palmitic acid | $C_{15}H_{31}COOH$ |
| Stearic acid | $C_{17}H_{35}COOH$ |
| Oleic acid | $C_{17}H_{33}COOH$ (one double bond) |
| Linoleic acid | $C_{17}H_{31}COOH$ (two double bonds) |
| Linolenic acid | $C_{17}H_{29}COOH$ (three double bonds) |

*Figure 9. Examples of fatty acids. Short-chain (volatile) fatty acids (VFA) have less than six carbon atoms in the molecule chain. Long-chain fatty acids (LCFA) often have well in excess of six.*

lation and the process "turning sour" because the VFA-degrading bacteria have a slow growth rate and cannot keep up. A steady degradation of VFAs is therefore crucial and often a limiting factor for the biogas process.

Hydrolysis of simple fats results in 1 mol glycerol and 3 mol LCFA. Larger amounts of fat in the substrate will thus result in large amounts of long-chain fatty acids, while large amounts of protein – that contain nitrogen in amino groups ($-NH_2$) – will produce large amounts of ammonium/ammonia ($NH_4^+/NH_3$). In both cases this can lead to inhibition of the subsequent decomposition phase, particularly if the composition of the biomass feedstock varies.

## METHANOGENESIS

The last step in the production of methane is undertaken by the so-called methanogenic bacteria or methanogens. The methanogens belong to a kingdom called Archaea, part of a taxonomic system that also comprises eukaryotes and bacteria at this level. A kingdom is the highest taxonomic level and Archaea are therefore at the same level as the other kingdoms – plants, animals, bacteria (Eubacteria), protozoa and fungi. Methanogens are believed to have been some of the first living organisms on Earth.

Two different groups of bacteria are responsible for the methane production. One group degrades acetic acid to methane and the other produces methane from carbon dioxide and hydrogen. Under stable conditions, around 70% of the methane production comes from the degradation of acetic acid, while the remaining 30% comes from carbon dioxide and hydrogen.

The two processes are finely balanced and inhibition of one will also lead to inhibition of the other. The methanogens have the slowest growth rate of the bacteria involved in the process, they also become the limiting factor for how quickly the process can proceed and how much material can be digested. The growth rate of the methanogens is only around one fifth of the acid-forming bacteria.

As previously mentioned, the methanogens do not release much energy in the process (see figure 10). But due to the anoxic conditions, the competition from other bacteria is limited, which is why they manage to survive.

| Source | Process | Energy yield kJ/mol methane |
|---|---|---|
| Hydrogen | $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$ | 131 |
| Formic acid | $4HCOOH \rightarrow CH_4 + 3CO_2 + 2H_2O$ | 145 |
| Methanol | $4CH_3OH \rightarrow 3CH_4 + CO_2 + H_2O$ | 105 |
| Acetic acid | $CH_3COOH \rightarrow CH_4 + CO_2$ | 36 |

*Figure 10. Energy yield of methanogens from decomposition of different sources.*

# PROCESS PARAMETERS FOR A BIOGAS PLANT

In order for a biogas process to be effective and productive, there are a number of parameters that have to be optimised.

## Anaerobic environment

As mentioned earlier, the methanogens need an oxygen-free environment – they are obligately anaerobic. A biogas reactor therefore has to be airtight. The small amount of oxygen dissolved in the liquid/biomass fed to the plant is quickly used up by, for example, aerobic bacteria that *must* have oxygen, or by facultative anaerobic bacteria that *can* use oxygen for their respiration, if it is present.

## Temperature

The rate of biochemical processes generally increases with temperature. As a rule of thumb, the rate is doubled for every 10-degree rise in temperature within certain limits ($Q_{10} = 2$). This is also the case with the biogas process. In this situation there are, however, several types or strains of bacteria involved that have adapted to the different temperatures:

psychrophiles   0 – 20°C
mesophiles    15 – 45°C
thermophiles  40 – 65°C

Common to the bacteria is that they are very sensitive to changes in temperature. This sensitivity increases with temperature. In practice, biogas plants are run at either a mesophilic level of around 37°C, where fluctuations of approx. ± 2°C are tolerated, or at a thermophilic level of around 52°C, where fluctuations of only approx. ± 0.5°C are tolerated.

## Acidity (pH)

Despite the methanogens using organic acids for some of their food intake, they cannot cope in an acidic environment. The optimum environment is a pH of between 6.5 and 8, and the preferred level is 7.2. When the process is in balance, the acidity in the reactor will be within this range and as the buffer capacity in the reactor is very large, it takes a lot to alter it. The system is, in other words, very robust and stable. Slurry-based plants often have a somewhat higher pH (8-8.3) due to a higher ammonium content.

## Substrate (feedstock)

Nearly all organic matter can be decomposed anaerobically, but the degree of decomposition can be increased in various ways. Lignin is, however, indigestible.

## Comminution

The finer the material, the larger the relative surface and the easier it is for the bacteria to attack the material.

## Dry matter content

For bacteria to be able to degrade the material, the dry matter content must not be higher than around 50%. In a biogas plant, however, it should only be around 8-10%, if it is to remain liquid enough to be pumped. A slightly higher level can be tolerated in special reactor types with a direct feed line.

## Carbon/nitrogen (C/N) ratio

Just like any other organism, methanogens need a number of macro- and micronutrients in order to grow (see figure 11). The most important macronutrients are nitrogen (N), phosphorus (P) and potassium (K). Nitrogen is used by bacteria to produce proteins. The nitrogen content is often quoted in relation to carbon, as this gives an indication of whether there is sufficient nitrogen available for bacteria. Normally the C/N ratio should be less than 30/1, as nitrogen otherwise becomes the limiting factor for bacterial growth. On the other hand, the nitrogen level should not be too high as this can then also inhibit the process.

| Essential micronutrients | Optimum concentration g/m³ |
|---|---|
| Barium (Ba) | 0.05 |
| Iron (Fe) | 0.2 |
| Calcium (Ca) | 0.03 |
| Cobalt (Co) | 0.005 |
| Magnesium (Mg) | 0.02 |
| Molybdenum (Mo) | 0.005 |
| Nickel (Ni) | 0.01 |

*Figure 11. Essential micronutrients in the biogas process and approximate optimum concentration. As with vitamins for humans, both too little and too much can be a bad thing.*

## Stirring

There are a number of different plant types, but for the most common type – CSTR (Continuously Stirred Tank Reactors) – the biomass has to be vigorously agitated to avoid the formation of an impenetrable surface crust.

COD = Chemical Oxygen Demand. The amount of oxygen used to degrade organic matter in water. COD is an expression for how much oxygen is needed to degrade organic matter to $CO_2$ and $H_2O$. It is mostly used to measure the organic loading of an aquatic environment. It is usually given in mg $O_2$/litre water. In biogas plants, the COD is given in kg/m³ = 1000 mg/L.

## Organic load

The rate at which biomass is added to the reactor has to be adjusted to the growth rate of the methanogens and organic acids have to be removed at the rate at which they are produced. The normal load for a CSTR reactor is 1-6 kg COD/m³ reactor volume/day.

If more biomass is added than the bacteria are able to degrade, the process will become acidic. The biomass also has to be fed to the reactor at an even rate and volume, preferably as a continuous feed. If the substrate has to be changed, this must be done gradually, so that bacteria can adapt to the new conditions.

# INHIBITION OF THE BIOGAS PROCESS

Inhibition means that a substance has a negative effect on bacteria without directly killing them. The process can be inhibited in many ways and the ways are often divided into endogenous and exogenous causes. Endogenous inhibition is due to conditions or material created during the process itself that under certain circumstances may inhibit the process, and exogenous inhibition is due to external conditions.

## Nitrogen inhibition

One of the most significant endogenous inhibitors is ammonia ($NH_3$). Ammonia is created during the bacterial degradation of nitrogen-containing substances such as proteins. Nitrogen is essential for bacterial growth and ammonia is an important source of nitrogen. But ammonia at high concentrations is highly toxic to the bacteria.

In an aqueous solution ammonia is always found in an equilibrium with ammonium ($NH_4^+$). This equilibrium is determined by the acidity, pH and temperature of the environment and, as ammonium is not as toxic as ammonia, this equilibrium is important:
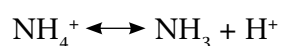
$$NH_4^+ \longleftrightarrow NH_3 + H^+$$

*Figure 12. Effect of pH and temperature on the balance between ammonium and toxic ammonia ($NH_4^+/NH_3$).*

At a high pH, the equilibrium is shifted to the right, and the environment becomes more toxic to bacteria. Higher temperatures will also shift this equilibrium to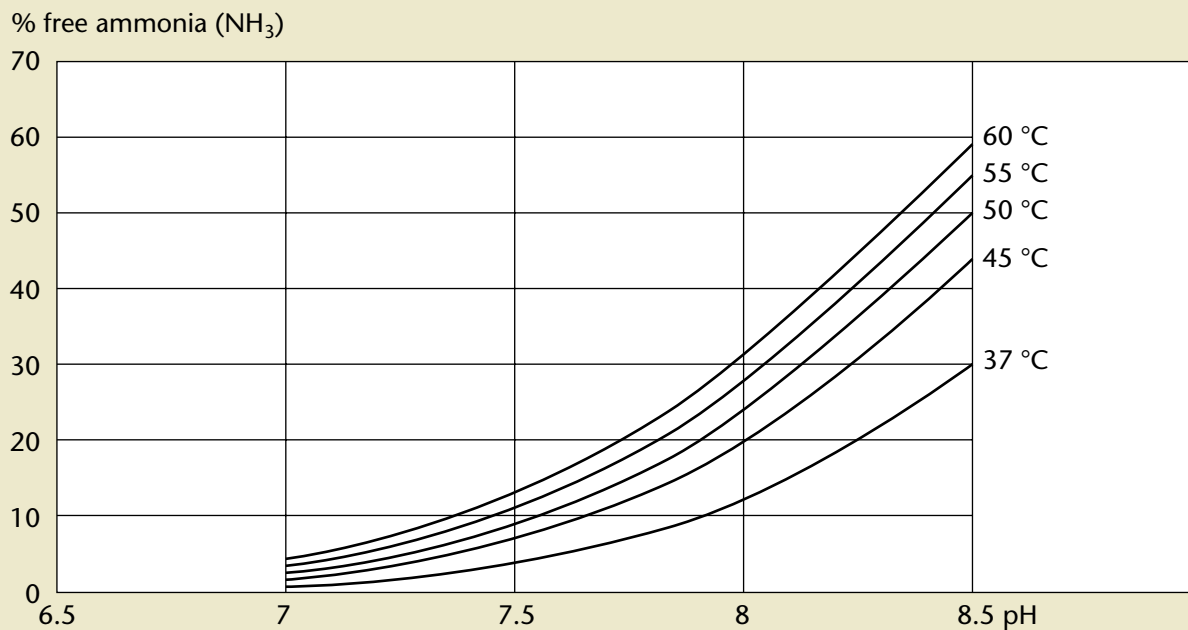 the right. This is why a thermophilic biogas process – all other things being equal – is more sensitive than a mesophilic process to ammonia inhibition (see figure 12).

There will be a certain inhibition of the bacteria already at relatively low ammonia concentrations. But with a longer adaptation period, bacteria are able to adapt to a higher concentration. This is fortunate, because the biomasses typically used in biogas production, such as slurry, usually have an ammonia concentration at the higher end of the scale. What the bacteria will have difficulties with is a sudden increase in the concentration, and a consistent and even input of biomass is therefore important for the process and even more so at higher temperatures.

## Acidification – organic acids

Other important endogenous process inhibitors are the organic acids formed during the process. If these are not removed as soon as they are formed – which can happen during an overload – this can lead to an acidification of the process.

## Antibiotics, etc.

Among the exogenous causes, antibiotics and disinfection agents are obvious inhibitors of the process, because both – by definition – are toxic to and are used to kill microorganisms. Both substances are used in livestock production to treat sick animals and to keep animal houses and milking parlous clean and can therefore also be found in the slurry, but apparently only at concentrations so low that they do not have a negative impact on the biogas plant. A slow adaptation to these substances can also take place if the supply is fed in continuously.

Other substances such as heavy metals, salts and micronutrients can also inhibit the process at high concentrations (see figure 13). But as previously mentioned, some of them are essential for the process at low concentrations, in the same way that vitamins are for humans (see figure 14).

13

| Chemical/formula | Inhibition level | Toxicity level |
|---|---|---|
| Ammonia, free, $NH_3$ | 50-100 mg N/l | 100-200 mg N/l |
| Ammonia, total, $NH_4^+ + NH_3$ | 1,000-6,000 mg N/l | 10,000 mg N/l (pH<7,5) |
| Chloride, $Cl^-$ | < 8,000 mg/l | 10,000 mg/l |
| Cyanide, $CN^-$ | 2-20 mg/l | 30 mg/l |
| Formaldehyde, $H_2CO$ | 100-400 mg/l | 500-1,000 mg/l |
| Phenol, $C_5H_5OH$ | 100-200 mg/l | |
| Chloroform, $CHCl_3$ | >1 mg/l (single dose) | >50 mg/l (continuous feed) |
| Hydrogen, $H_2$ | $p(H_2)$ ca. $10^{-4}$ atm. | |
| Copper, $Cu^{+++}$ | 10-250 mg/l | |
| Chrome, $Cr^{+++}$ | 50-100 mg/l | 200-400 mg/l |
| Nickel, $Ni^{++}$ | 100-200 mg/l | 300-1,000 mg/l |
| Sodium, $Na^+$ | 3,000-10,000 mg/l | |
| Calcium, $Ca^{++}$ | 8,000 mg/l | |
| Magnesium, $Mg^{++}$ | 3,000 mg/l | |
| Zink, $Zn^+$ | 350-1,000 mg/l | |
| Sulphate, $SO_4^-$ | 500-4,000 mg/l | |
| Sulphide, (as sulphur) | 200 mg/l | |
| Hydrogen sulphide, $H_2S$ | 250-1,000 mg/l | |

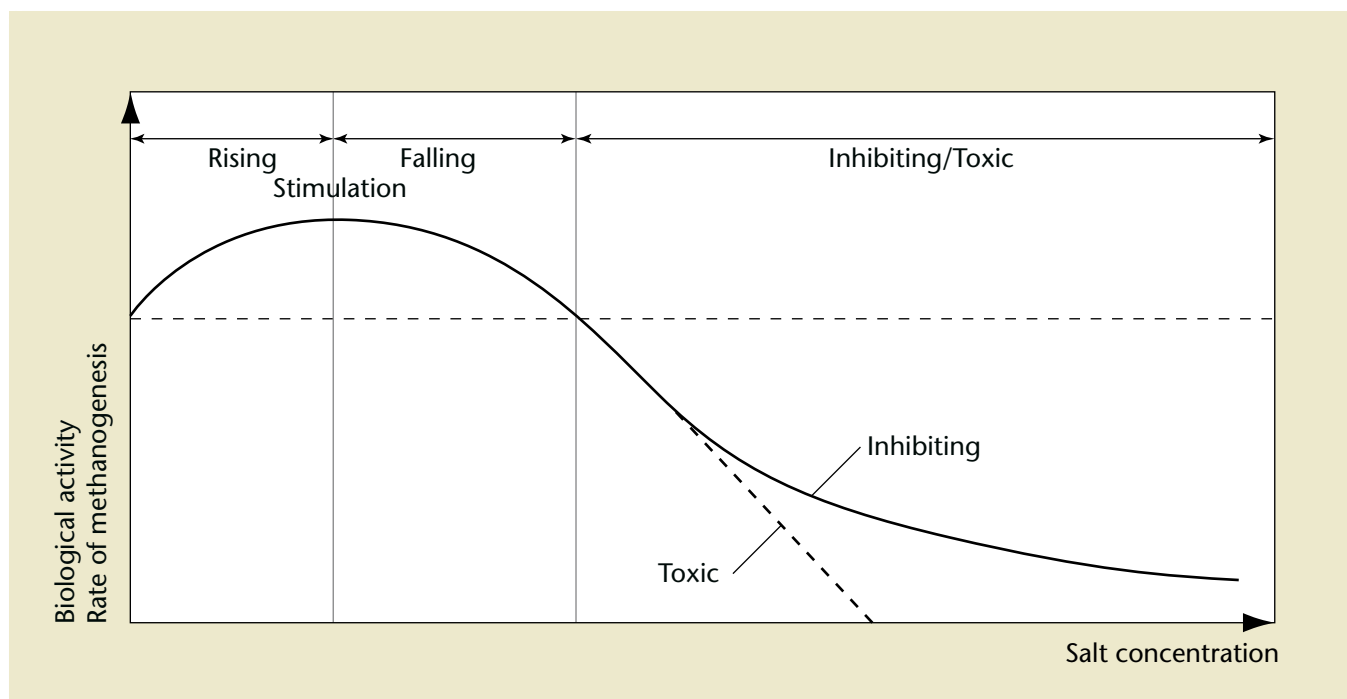Figure 13. Selected inhibitors with values at which they are inhibiting and toxic.



Figure 14. Salts can both stimulate and inhibit the biogas process. When exactly inhibition starts depends on the salt concentration. Some salts have a directly toxic effect at high concentrations.

# BIOGAS PLANT DESIGN

There are a number of different types of biogas plants that can be used to treat different types of biomass, and each has its advantages and shortcomings. However, Danish farm and communal biogas plants only use the CSTR – continuously stirred tank reactor.

The CSTR has the advantage that it can treat biomasses with a relatively high dry matter content. The biomass is fed into the reactor continuously or semi-continuously in regular batches. To make room for the new biomass input, some material has to be pumped out first, and due to the continuous stirring, this means that some of the recently added, fresh biomass is pumped out again too quickly and before it is fully decomposed, which is the greatest drawback with this type of reactor.

In industry, so-called filter plants are sometimes used such as those using UASB (Upflow Anaerobic Sludge Blanket), which can treat biomasses with a low dry matter content. The advantage of this type is that the (hydraulic) retention time (the time a given biomass stays in the reactor before it is pumped out again) is very short, often only a few hours or a couple of days, and that the reactor tank therefore does not need to be quite so large. This type can also take a relatively high COD load of 5-30 kg COD/$m^3$/day.

In the following, only the fully stirred plant type will be discussed, as this is the type most commonly used in Denmark for the decomposition of both agricultural residues and sewage sludge.

In principle, both on-farm and communal plants have similar designs, but some parts will obviously be of different size depending on, for example, how much biomass they are meant to handle. In the following we describe a typical communal plant (see figure 15). The plant can be divided into a biomass system and a gas system.
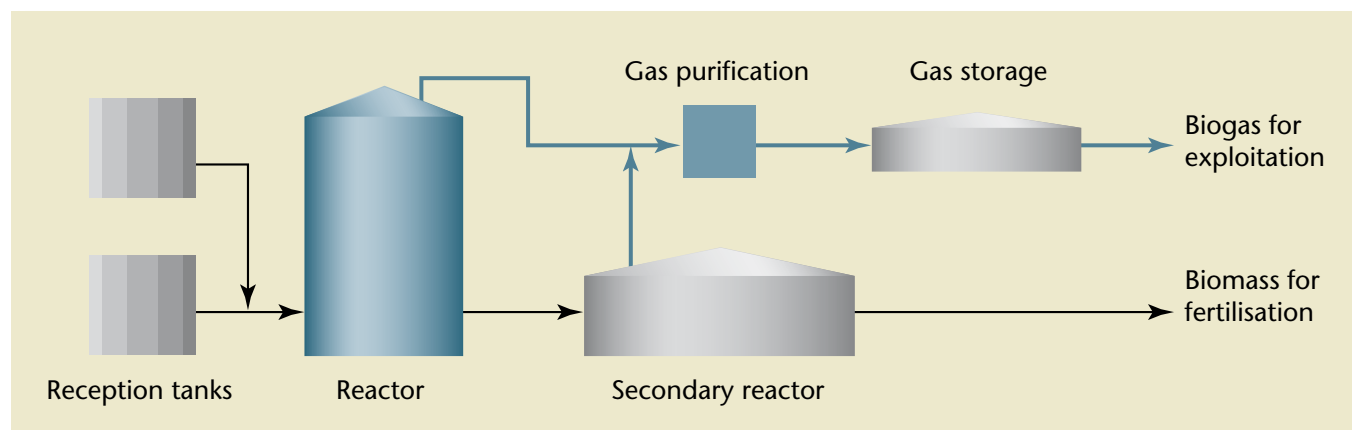


*Figure 15. Schematic diagram of a communal biogas plant. The animal manure enters the system in the reception tanks. It is then pumped to the reactor where the digestion and biogas production take place.*

# Biomass system



## Reception tank

Typically a couple of reception tanks are used: One for slurry and manure and one for other types of biomass such as organic industrial waste. The purpose of the reception tank is to act as a buffer tank to ensure the plant will also run at weekends and during holidays. Different biomasses are moreover mixed in the reception tanks to ensure the biomass fed to the reactor is homogenous. Slurry reception tanks typically have sufficient storage capacity for seven days and are often covered concrete tanks. Reception tanks for industrial waste often have a larger capacity. The tanks are fully stirred to prevent the formation of layers, and in certain cases the reception tank for industrial waste is heated to ensure, for example, that the fatty part stays liquid. In the slurry reception tanks a large amount of sand and grit may settle out and that has to be removed from time to time.

Some systems incorporate a mixer tank between the reception tanks and the reactor.

The reception tanks can give off various odorous compounds. These can be extracted and cleaned with different air purification systems.

## Biomass feeding pump

A pump moves the biomass from the reception tank to the reactor tank. The pump can be immersed in the reception tank or sit in its own pump well. The pump often has an associated comminutor, which shreds the biomass.

## Reactor tank

The reactor tank is a completely enclosed and insulated steel tank or a concrete tank covered by an airtight seal. The tank can be fitted with heating coils that warm the digesting biomass, or the heat supply can be external via a heat exchange system. The tank is equipped with a stirrer that can keep the entire volume fully agitated and thus prevent the formation of a surface crust. It is also equipped with an overflow outlet, temperature and pressure gauges, etc. There is, finally, a high-pressure valve to ensure that the pressure does not become unacceptably high if the gas removal fails. At the top of the tank there is an outlet for the biogas produced.

The reactor tank typically has a volume of 10-20 times the daily input of biomass for a thermophilic process and 15-25 times the daily input for the mesophilic process.

**Effluent discharge pump**

A pump moves the digested biomass to a storage tank. In simple plants, and with a suitable arrangement of pipes and valves, one pump can take care of both the feeding and discharge.

## THE GAS SYSTEM

### Gas condensation

The biogas produced in the reactor and secondary digester (if used) is extracted. The gas is warm and therefore contains a large amount of water vapour. When cooled, most of this water will condense out and can then be pumped back to the secondary digester.

### Gas purification

Besides methane and carbon dioxide, the gas also contains a smaller amount of hydrogen sulphide ($H_2S$). The amount is proportional to the protein content of the biomass. The higher the protein level, the higher the $H_2S$ production. If the biogas is intended to be used in a combustion engine, the $H_2S$-content has to be removed from the gas, as it is corrosive in combination with $CO_2$ and water vapour. This can be done in a biological process, where the ability of sulphur bacteria to degrade hydrogen sulphide to pure sulphur or sulphuric acid is utilised. This sulphur in an aqueous solution is pumped to the secondary storage tank and therefore recycled to the field and crops.



**Digestate storage tank**

The purpose of the storage tank (or secondary digester) is to act as a buffer tank before the digested biomass can be transported away to be finally stored in the farmer's own storage tank or applied as fertiliser directly on farmland.

The tank is usually covered, partly to prevent the entry of rainwater and partly to prevent the loss of ammonia. If there is a long retention time, there will additionally be a certain amount of gas produced from the storage tank as the biomass in a fully stirred reactor will never be completely digested. This gas can also be extracted and used.



**Gas storage**

In order to even out the gas production, most plants also have a gas store with capacities ranging from two to 24 hours of production. Biogas takes up a lot of space and it is rarely worth having a large storage capacity.

**Gas transmission**

At several plants the purified gas is subsequently pumped from 5-10 km in a gas transmission pipe to a local combined heat and power plant, where the biogas may replace natural gas.

# END USES OF BIOGAS



*The farm biogas facility on the island of Orø produces electricity and heat both for the farm itself and for a nearby institution. The shiny cylinder in the foreground is a silencer.*

**B**iogas is flammable and can therefore be used both in energy production and transport. The taxes levied on the fuel it replaces usually determine what the end use of the gas will be.

The simplest use of the gas is in a gas boiler, where the gas produces heat that can be used for heating purposes. The efficiency (annual efficiency rating) is approx. 85%. With this type of application, the fuel that is typically replaced is heating oil. The method is currently only used on smaller plants.

Under Danish conditions it usually makes better economic sense to use the gas to drive an engine generator system. The engine can be an ordinary combustion engine. The engine drives a generator that produces electricity. Residual heat from the engine and from the flue gas system can be captured and used for heating purposes.

Of the total energy content of the biogas, 30-40% is typically converted into electricity that can be sold to the grid and 45-55% is converted to heat (less the heat used in the process) that can be sold to, for example, a smaller central heating plant. The relationship between how much is converted to electricity and how much to heat depends on the size of the engine. The overall conversion efficiency is usually about 85%. At this efficiency level, biogas can replace both coal in power stations and the fuels used by a heating plant (oil, natural gas or biomass).

The biogas can also be used for transport and for this purpose the carbon dioxide is often removed from the gas to reduce its volume. The transport option is not used in Denmark, but is widely used in Sweden where bioenergy taxation levels are more favourable for this end use. This end use replaces liquid fuels such as petrol or diesel.

# GAS YIELD OF DIFFERENT BIOMASSES

As mentioned earlier, all organic matter, with the exception of lignin, can be decomposed anaerobically to produce biogas, although the time taken to do so differs greatly. How long it takes depends on the composition of the biomass – the more complicated the molecules, the longer it takes a microorganism to break it down.

Sometimes a biomass consists of a number of different substances that have an impact on the gas yield. Figure 16 shows the biogas and methane yield when carbohydrates (cellulose), proteins and fats are completely digested. The table shows that the gas yield is about twice as high for fat as for protein and carbohydrate.

The table also shows that the composition of a biomass – the ratios between carbohydrate, protein and fat – has an effect on how much methane the biomass contains and therefore on its calorific value. The methane content from a biogas plant where the input is mainly animal manure is typically around 65%, which is because there is some $CO_2$ in solution in the alkaline liquid. The methane content of landfill gas can be as low as 50%.

The biogas yield of a biomass is actually quite precisely defined: the conversion of 1 kg COD (that is, the amount of organic matter that consumes 1 kg $O_2$ at a total digestion) produces precisely 0.35 $m^3$ methane at normal temperature and pressure. Unfortunately, a biomass is rarely completely digested, or at least it takes a very long time and cannot be relied on in practice as the reactor size is limited and the average retention time will, therefore, also be limited. Figure 17 shows an example of the level of digestion achieved of different substances in pig slurry under normal process conditions.

Extending the retention time will naturally increase the level of degradation, while a shorter retention time will result in a decrease. The last three substances in the table - the polysaccharides – are the most important for biogas production, as they are the main constituents of most biomasses.

| Organic substance | Process | Gas yield, STP [1] | | CH$_4$ |
|---|---|---|---|---|
| | | ml biogas/g | ml CH$_4$/g | % |
| Cellulose | $(C_6H_{10}O_5)n + nH_2O \rightarrow 3nCH_4 + 3nCO_2$ | 830 | 415 | 50.0 |
| Protein | $2C_5H_7NO_2 + 8H_2O \rightarrow 5CH_4 + 3CO_2 + 2(NH_4)(HCO_3)$ | 793 | 504 | 63.6 |
| Fat [2] | $C_{57}H_{104}O_6 + 28H_2O \rightarrow 40CH_4 + 17CO_2$ | 1,444 | 1,014 | 70.2 |

Figure 16. Biogas and methane yield at a complete digestion of carbohydrate (cellulose), protein and fat.
[1] STP = Standard Temperature and Pressure (0°C and 1 atm.). [2] Glycerol trioleic acid.

| Substance | Level of digestion, % |
|---|---|
| Organic matter (VS) | 60 |
| Protein | 47 |
| Fatty acids, lipids | 69 |
| Hemicellulose | 65 |
| Cellulose | 69 |
| Starch | 94 |

Figure 17. Level of digestion of different substances in pig slurry. Organic matter is stated as volatile solids (VS – the organic, decomposable part of dry matter).

19

# Measuring gas yield

The gas yield of a biomass is often determined by laboratory digestion in a batch reactor. A measured sample is poured into a flask, inoculated with a culture of anaerobic bacteria and put into a water bath and stirred at constant temperature. A control flask containing only the inoculate is run in parallel, and the gas production from both is measured over a longer period. By subtracting the gas produced by the control flask from that produced by the test flask, the production from the biomass is calculated. Figure 18 shows a laboratory setup to measurement of biogas.

The experiment provides information on the accumulated gas production. When daily measurements are summed and if the period is long enough, you end up with a figure that is close to the potential total gas production of the biomass. If the methane element in the biogas is also determined, the accumulated energy potential can be worked out.

If you then draw a graph over the accumulated gas production, you get a picture of how fast the biomass digests. This will determine the size of reactor to be built, but as reactor volume is expensive to establish and the reactor therefore, in practical terms, cannot be made large enough to allow the biomass to fully digest, you have to make do with less. How long the retention time should be depends on economic considera-

tions – in other words the value of the extra gas produced compared to the extra cost involved in building a larger reactor. Figure 19 shows the accumulated biogas production at 30°C of different typical biomasses.

The graph shows, first of all, that there are large differences in the biogas potential of the different biomasses with some requiring a very long digestion time to get close to the 100% potential. The graph also shows that some biomasses are digested considerably faster than others. This is the case, for example, for grass. Finally, the graph shows that it takes a couple of days for the process to get started. There is, in other words, a shorter or longer adaptation period for the bacteria. At higher temperatures the graph will typically be steeper than in figure 19 and it will take less time for the near-full potential to be reached.

# Digestion in practice

In practice, the digestion is, as previously mentioned, a continuous process. This means that, on the one hand, there will be no adaptation period needed for the bacteria if the biomass composition is constant. On the other hand, the daily in- and outflow of biomass from the reactor means that in a fully stirred reactor some of the biomass pumped out will have spent a relatively short time in the reactor.

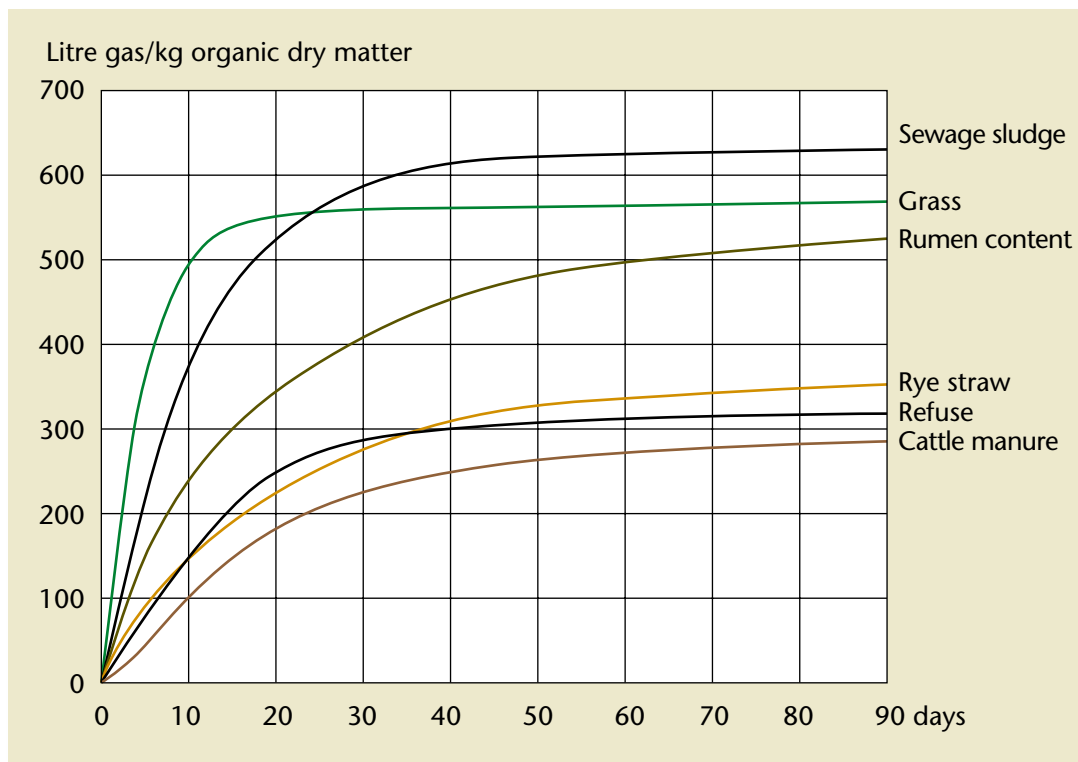*Figure 18. Laboratory setup to measurement of biogas.*

Figure 19. Examples of biogas yield with batch digestion of different organic materials at 30°C.

Figure 20 shows the amount of biomass pumped in on day 1 that theoretically remains in the digester with time when there is a daily outflow of biomass. Basic assumptions are: an average retention time of 20 days, a fully stirred reactor, that one twentieth of the biomass is replaced every day by the daily in- and outflow. As the figure shows, about 20% of the biomass pumped into the reactor on day 1 will have been pumped out again already after five days. This biomass will therefore not be fully digested. However, about one third of the biomass will still be in the reactor after 20 days.

This relationship is naturally important for how much of the theoretically potential gas production of the biomass can be achieved before the biomass is pumped out again, and this also means that the gas production is
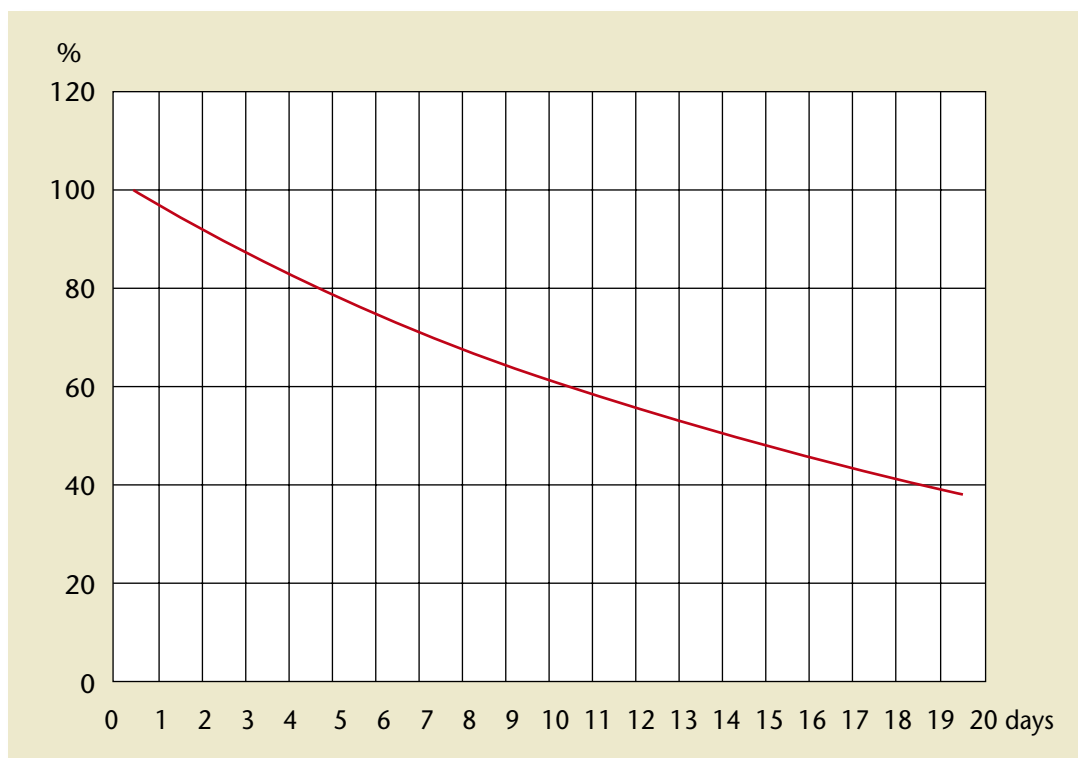


Figure 20. The amount of biomass pumped in on day 1 remaining with time. The average hydraulic retention time is 20 days, so one twentieth is replaced every day.

not constant over time (see figure 19). For the biomasses that are quickly digested it is less important than for the biomasses that require a longer retention time.

There are several ways of reducing this problem and to achieve a somewhat better digestion efficiency. In practice, the biomass is pumped from the reactor to a storage tank, where the biomass is stored for a period. In many biogas systems this tank is covered and used as a secondary reactor. Depending on the biomass, temperature and retention time, this secondary reactor can achieve an additional gas production of 5-15% of that of the primary reactor. Some manufacturers consequently incorporate a smaller secondary reactor in the system.
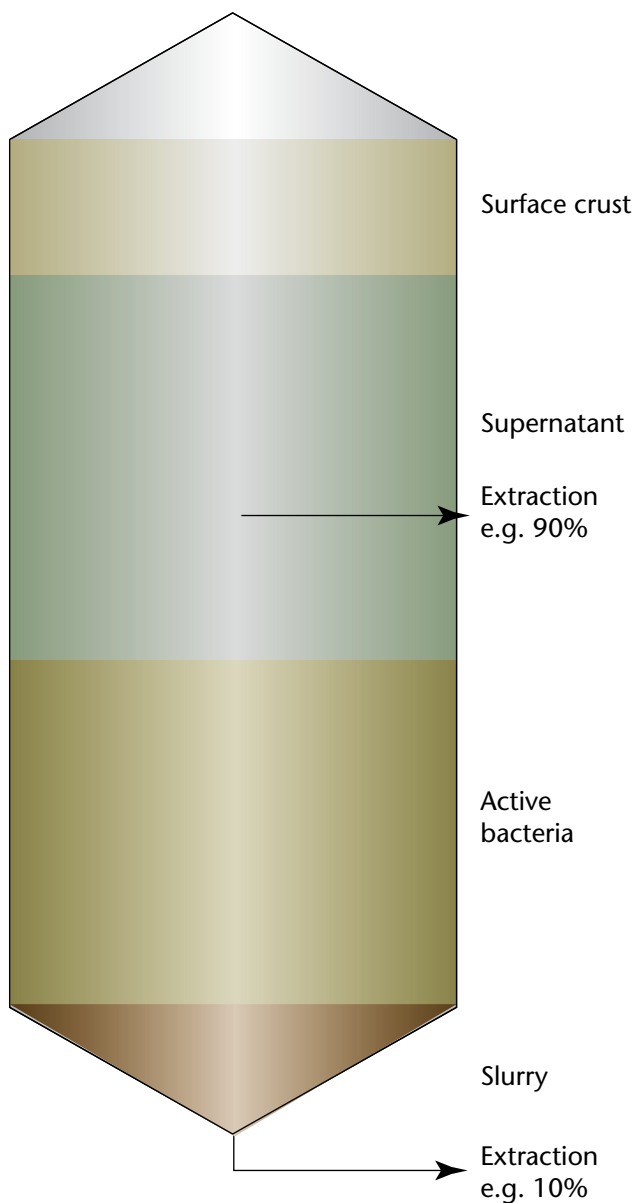
By separating the digested biomass with, for example, a decanter centrifuge (see page 32) and recycling the fibre fraction to the reactor, the retention time can be extended for the benefit of the slowly decomposing materials, such as straw. Whether this is a good idea depends on the relationship between the extra costs incurred and the extra gas yield achieved, and on whether the space taken up by the material could have been better used by a material with a greater gas potential.

Finally, there is a third method based on a special pumping strategy that utilises special hydraulic relationships in the reactor. If the mixing in the reactor is stopped, the biomass relatively quickly separates into four layers (see figure 21). At the surface a crust is formed consisting of lighter materials. Next comes a layer of supernatant, which primarily consists of water with little in the way of suspended matter. This is followed by a layer of active bacteria and, finally, there is a slurry layer with the heavier particles (sand, minerals, etc.). If the pump-out is mainly from the supernatant layer, the particles and substances that form the surface crust can be kept in the reactor for a longer time. In addition, you do not run the risk of pumping out bacteria from the active layer and reducing their concentration in the reactor.

In this manner some of the organic matter will end up having a longer retention time and you will, therefore, achieve a higher gas yield per kg organic biomass (VS).

In practice, the method is not that easy to control. Firstly, some of the slurry needs to be removed at regular intervals in order to avoid the build-up of sand. This is best done by pumping, say, 10% out from the bottom of the reactor and the rest from the supernatant layer. It is, however, more problematic that the surface crust gradually thickens and that at some point it becomes so dense that the stirrers can no longer keep the mixture stirred. If this is allowed to happen, the process will die. If pumpouts take place at regular intervals, it is possible to avoid this, but as you cannot see from the outside how thick the crust has become and as it is also difficult to measure, getting the right concoction of biomasses will be a question of trial and error. Only few plants are therefore constructed to use this principle.



Surface crust

Supernatant

Extraction
e.g. 90%

Active
bacteria

Slurry

Extraction
e.g. 10%

Figure 21. Stratification in reactor during a mixer stop.

| Biomass | Typical gas yields | | Methane % | VS % of TS |
|---|---|---|---|---|
| | m³ biogas/ kg DM | m³ methane/ kg VS | | |
| Pig slurry | 0.37 | 0.32 | 65 | 75 |
| Cattle slurry | 0.24 | 0.21 | 65 | 75 |
| Mink slurry | 0.40 | 0.35 | 65 | 75 |
| Deep bedding | 0.24 – 0.37 | 0.21 – 0.32 | 65 | 75 |
| Chicken manure | 0.40 | 0.35 | 65 | 75 |
| Flotation sludge from sewage treatment plant | 0.41 – 0.86 | 0.36 – 0.75 | 70 | 80 |
| Offal | 0.49 – 0.57 | 0.40 – 0.46 | 65 | 80 |
| Primary sludge | 0.38 | 0.33 | 65 | 75 |
| Biological sludge | 0.11 – 0.23 | 0.10 – 0.20 | 65 | 75 |
| Source-separated household waste | 0.43 | 0.35 | 65 | 80 |
| Maize | 0.61 | 0.37 | 55 | 90 |
| Grass | 0.57 | 0.35 | 55 | 90 |

*Figure 22. Gas yield from different biomasses. DM is the dry-matter weight of the biomass; VS is the organic biomass (volatile solids).*

# BIOGAS POTENTIALS

As the above shows, the biogas yield of a given biomass is not a fixed value, but depends on factors such as temperature and retention time in the reactor. And as previously mentioned, a number of micro- and macronutrients also have to be present in the right amounts. It is thus not possible to digest, for example, fats or sugars on their own.

Neither is it beyond imagination that there may be some synergetic effects when different biomasses are mixed – that is, that the production achieved is larger than the sum of the individual potentials. The opposite can also be true.

Listed below are some of the biomasses that to a smaller or larger extent are used today. The list is, however, not conclusive and others may also be used. Figure 22 shows the typical gas yields of different biomasses.

## Animal manure

The largest underutilised resources for biogas production are found in agriculture. Approx. 4-5% of the animal manure produced is currently used for biogas production, corresponding to just over 1.2 million m³/year. It is naturally not realistic to expect to achieve a 100% utilisation, but a much higher usage would bring definite benefits to the environment.

## Industrial waste

Existing biogas plants also take in considerable amounts of organic industrial waste from the food industry including slaughterhouse waste. The amount is estimated at around 350,000 t/year and the arrangement can be seen as an example of an effective and sustainable recycling of resources. In this case, the organic matter is used for energy production and the nutrients are recycled to agricultural land to replace commercial fertiliser. This resource also contributes significantly to making the biogas plants viable, partly because the waste often has a high gas potential (high DM and fat content) and partly because the plant often charges a gate fee for handling it.

The amount of industrial waste available in this country is, however, nearly fully utilised, which means we are now importing some of the waste for biogas production.

In any future expansion of sewage treatment facilities, it is advisable to opt for the anaerobic process that produces energy rather than the aerobic process that uses energy.

## Sewage sludge

Much of the sewage sludge currently produced is already being digested at sewage treatment plants around the country. In certain instances, it may be possible to redirect the sludge to biogas plants and thus ensure a better digestion of the sludge and, not least, a recycling of the nutrients to farmland. But this is a bit of a problematic issue. Some food producers, for example, do not allow digested, sludge-containing biomasses to be applied to land used for food production, even if the biomass complies with all environmental regulations. The reason is not logical or based on environmental considerations. Food producers simply fear the reaction of consumers, because consumers do not always react rationally. The word 'sludge' has, in the public ear, a negative ring to it and then it is immaterial that the practice is well regulated and sustainable – companies dare not run the risk for fear of a consumer boycott.

## Household waste

Household waste can also be used in biogas production and has previously been used in several plants. In some plants this is still the case, but most have stopped the use, either due to problems with the sorting resulting in too many impurities (knives and forks, plastic bags, etc.) that upset the digestion process, or due to problems with smell. This disposal route must, however, still be regarded as the most sustainable, again due to the scope for energy extraction and recycling of nutrients.

## Energy crops

In recent years the use of energy crops has become increasingly interesting partly because of the limited supply of organic industrial waste. Virtually all arable crops can be used, as can crop residues such as turnip and potato tops. The only requirement is that the crop must be
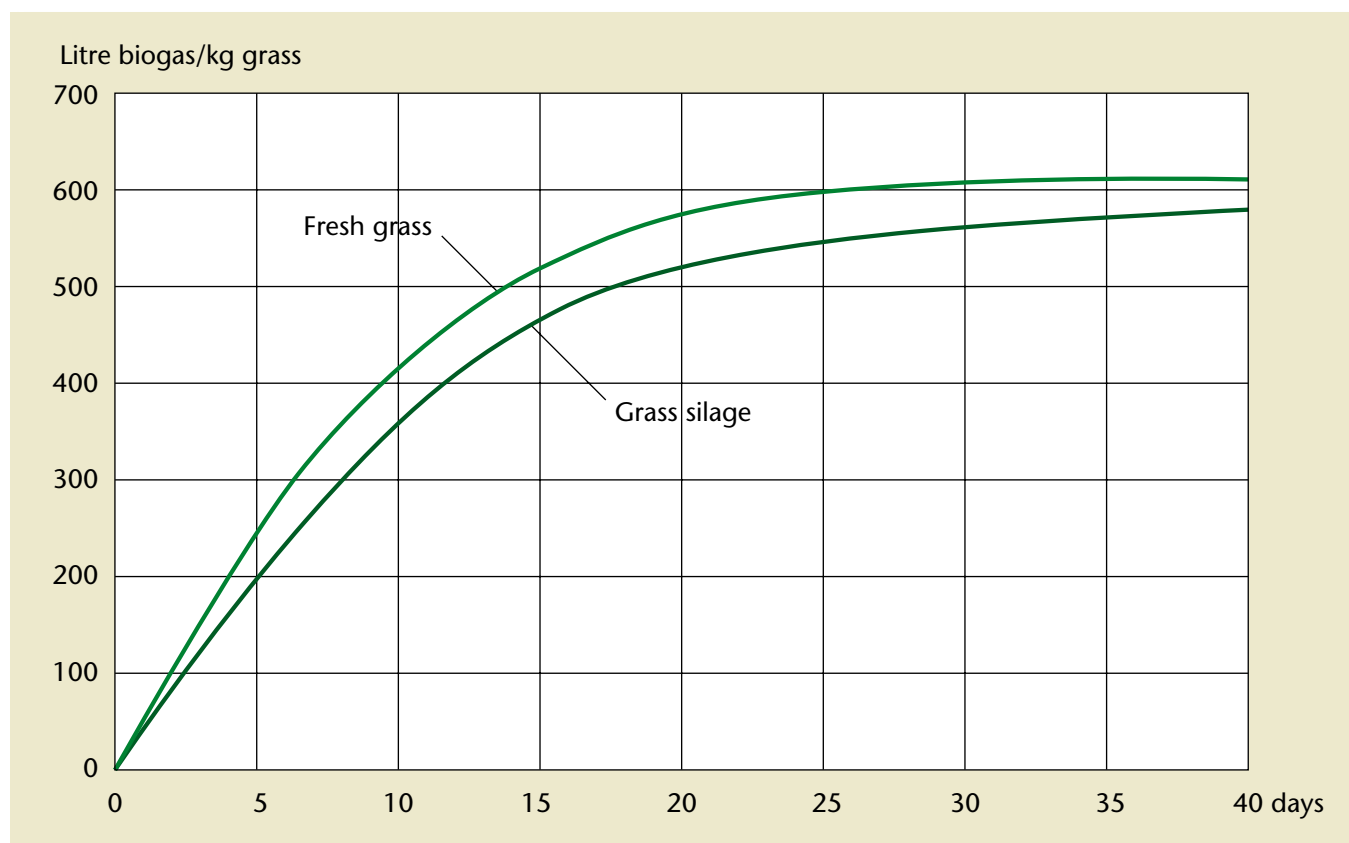


*Figure 23. Gas yield from the fermentation of fresh grass and grass silage.*

relatively easily digestible. In other words, the material must not contain too much lignin. The potential is huge – it is simply a question of how much land you wish to put down to energy crops. One exciting aspect of growing energy crops is that their cultivation can be more environmentally friendly than that of traditional crops. This is true particularly for perennial crops such as permanent grass, and they could therefore be used to reduce problems with the leaching of nitrogen in sensitive areas. The biomass can be either freshly cut or in the form of silage. This means that some can be stored for use during the winter months (see figure 23).

The growing of legumes such as grass-clover, lucerne, or broad beans can provide an additional source of nitrogen to the crop rotation via the ability of these plants to fix nitrogen in their roots. In this way, less mineral fertiliser again needs to be used, which can improve the energy balance of their cultivation even further as the production of mineral-N is very energy-demanding. With the right crop, careful planning and control, energy crops therefore offer a potentially high bioenergy output and also an effective protection of the environment against the leaching of nitrogen.

Some people, nevertheless, see an ethical dilemma in growing energy crops on farmland when there are so many starving people in the world. But if you are thinking along these lines, you should perhaps also consider whether it is ethical to produce and eat such large quantities of animal products as we do. This also requires the use of vast areas of agricultural land that could alternatively have been used for the production of food crops. And, finally, it will not be the first time in history that a large proportion of farmland is put aside for non-food crops. Only 60-70 years ago up to 20% of farmland was used to produce feed for the country's well-developed transport system: horses.

## CURRENT BIOGAS PRODUCTION AND FUTURE POTENTIAL

Figure 24 shows the current production and the estimated future biogas potential for a number of biomasses.

The current production covers approx. 5‰ of the Danish energy consumption. At full utilization of the resources, energy crops could cover 6-7% of the consumption. Animal manure tops the list of resources, but from an economic and environmental viewpoint, animal production may increasingly be expected to be moved abroad and could thus contribute less in the future. Energy crops, on the other hand, are a flexible resource and their future use will, to a large extent, be determined by environmental and economic conditions.

| Unit, PJ | Production in 2004 | Potential |
|---|---|---|
| Animal manure | 0.91 | 26.0 |
| Sewage sludge | 0.91 | 4.0 |
| Industrial waste, Danish | 0.86 | 2.5 |
| Industrial waste, imported | 0.65 | ? |
| Meat and bonemeal | 0.0 | 2.0 |
| Household waste | 0.03 | 2.5 |
| Landfill gas | 0.46 | 1.0 |
| Energy crops [1] | – | 15.9 |
| **Total** | **3.82** | **53.0** |

*Figure 24. Biogas production (2004) and estimated potential for a number of biomasses.*
[1]*Assumptions: 5% of farmland, 10 t DM/ha, 90% VS, 0.35 $m^3$ $CH_4$/kg VS.*

# BIOGAS AND THE ENVIRONMENT



*Lemvig Biogas Plant. Using biogas reduces $CO_2$ emissions.*

## CLIMATE CHANGE

### $CO_2$-emission

The use of biogas and biomass as an energy source is regarded as $CO_2$ neutral because the $CO_2$ released during combustion of the biogas is the same $CO_2$ that the plants in the biomass have assimilated during photosynthesis to create organic matter. In this way the burning of biogas is simply a recycling of $CO_2$ in the biosphere.

In addition to this, the energy production itself also helps reduce the emission of greenhouse gases, the magnitude depending on which fuel is being replaced. If biogas is used instead of straw, there will be no reduction in $CO_2$ emissions, because the use of straw is already $CO_2$ neutral. If, however, biogas replaces oil, less oil will be used and there will be a reduction in emissions. There will likewise be a different set of reduction figures if the biogas is used for transport purposes and replaces diesel or petrol.

At most Danish communal biogas plants the biogas is used for electricity production via the use of an engine-generator. The electricity, which constitutes 35-40% of the energy content of the biogas, is sold to the grid and replaces electricity that would otherwise have been produced at one of the large coal-fired power stations.

According to figures published by the Danish Energy Agency, atmospheric emissions are reduced by 640 g $CO_2$ for every kWh electricity produced from biomass and wind. And this is not the only saving, as there is also a reduction

| Maximum CO₂ replacement<br>**Biogas heat and power cogeneration** | g CO₂ per. m³ biogas,<br>**65% methane** |
|---|---|
| Electricity production[1], 2.5 kWh/m³ | 1,600 |
| Heat production[1], 1.5 kWh/m³ | 400 |
| **Total** | **2,000** |

*Figure 25. Maximum $CO_2$ replacement if biogas is used instead of coal for electricity and heat production. [1]Surplus after own consumption of heat and electricity.*

in slag and ashes of 38 g. As 1 m³ biogas produces 2.5 kWh electricity, the $CO_2$ reduction will be 1,600 g/m³ biogas (see figure 25).

In addition to electricity, the engine produces heat that can be extracted, partly from the cooling system (low-temperature heat, 70-80°C), and partly by cooling the flue gases (high-temperature heat, 150-200°C). Approximately 45-50% of the energy content of the biogas can be extracted as heat (see figure 26).

Some of the heat produced is either used as process heat for heating the biomass, is lost or is used elsewhere on the plant (heat needed to heat the biomass: 1.163 kWh/m³/°C + heat loss). Approximately half of the heat produced will be available for other heating purposes. Again – if the fuel replaced is fuel oil, the reduction in emissions will be considerable, namely 266 g $CO_2$/kWh, i.e. 400 g for every m³ of biogas used for heat production. But if the biomass displaced is straw, the reduction will be negligible (see figure 25).

If you would like to calculate more precisely the $CO_2$ displacement for a given biogas project, you have to take into account the actual supply situation and the fuels that will be displaced.



## Biogas 100%
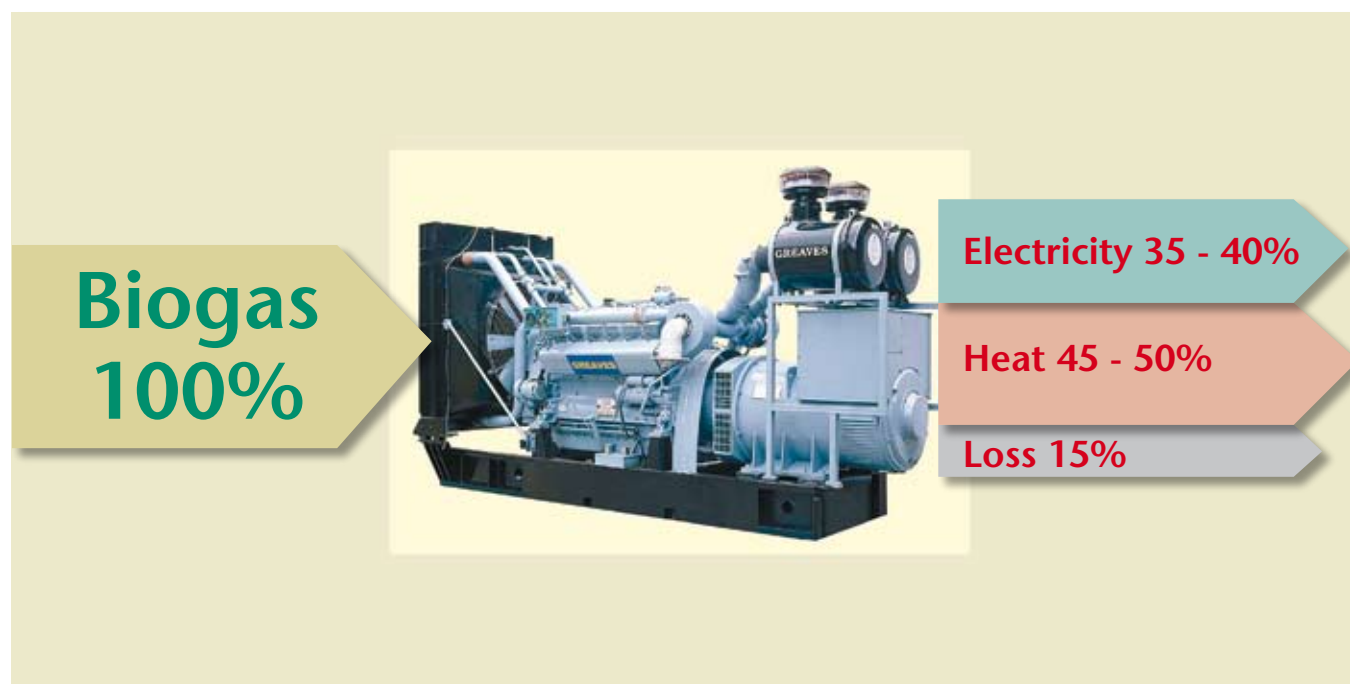
Electricity 35 - 40%

Heat 45 - 50%

Loss 15%

*Figure 26. The efficiency of converting biogas to energy. The heat can be sold off to be used for heating and the electricity can be sold to the grid.*

27

## Emissions of methane and nitrous oxide

As previously mentioned, methane is a greenhouse gas that contributes significantly to the enhanced greenhouse effect, and the concentration of methane in the atmosphere is rising at an annual rate of approximately 1%. About half of this rise in the EU is thought to originate from agriculture where the largest sources are farm animal digestion and handling of animal manure.

To be able to compare methane ($CH_4$) and nitrous oxide ($N_2O$) to $CO_2$, methane and nitrous oxide are usually converted to $CO_2$-equivalents ($CO_2$-eqv.) when assessing their global warming potential. One kg $CH_4$ corresponds to approx. 22 kg $CO_2$, while 1 kg $N_2O$ corresponds to approx. 310 kg $CO_2$.

$N_2O$ thus has a global warming potential that is 310 times larger than that of $CO_2$, and very little additional $N_2O$ is therefore needed for the greenhouse effect to be adversely affected. The concentration of $N_2O$ in the atmosphere is currently rising at a rate of 0.3% per year, and, here too, agriculture is responsible for about half. $N_2O$ is primarily formed by the conversion of nitrogenous fertilisers on farmland under anaerobic conditions and in the presence of easily degradable organic matter. The main process involved here is denitrification.

Anaerobic digestion of slurry in biogas plants reduces the manure's content of easily degradable matter due to the production of biogas. During subsequent storage, less methane will therefore be released from the farmer's storage tank and less nitrous oxide will be released in the field when the slurry is later used as a fertiliser.

## TOTAL $CO_2$ REDUCTION POTENTIAL WITH BIOGAS PRODUCTION

Model calculations show that the digestion of animal manure in a biogas plant reduces the emission of greenhouse gases by approx. 0.3 and 0.6 kg $CO_2$-eqv./kg organic matter for, respectively, pig and cattle slurry. With an equal mixture of cattle and pig slurry with, respectively, 10 and 5% DM and 75% VS, this corresponds to a reduction in the emission of greenhouse gases of approx. 26 kg $CO_2$-eqv./m³ biogas produced. On this basis, you can calculate the theoretical potential for reducing the emission of greenhouse gases in Denmark with an efficient use of biogas technology (see figure 27).

**Total potential reductions in greenhouse effect with biogas production**

| Biomass | Amount | Biogas production | $CO_2$-reducion with CHP production - optimal use | $CH_4$ and $N_2O$ reduction as $CO_2$-eqv. | Total Reduction as $CO_2$-eqv. |
|---|---|---|---|---|---|
| | (million t/yr) | (million m³/yr) | (tons $CO_2$/yr) | (t $CO_2$/yr) | (t $CO_2$/yr) |
| Animal manure | 15 [1] | 330 [3] | 660,000 [4] | 390,000 [5] | |
| Organic waste | 0.5 [2] | 25 [3] | 50,000 [4] | 100,000 [6] | |
| **Total** | **15.5** | **355** | **710,000** | **490,000** | **1,200,000** |

- The Kyoto Protocol commits Denmark to a reduction of 25 million t $CO_2$/yr.
- Biogas production based on animal manure and waste can thus contribute approx. 5% of this.

Figure 27. Annual potential biogas production and $CO_2$ reduction using animal manure and organic waste. The energy crop option has not been included.
Assumptions:
1) Total animal manure production in Denmark: 30 million t. Half of this is used in biogas production.
2) Annual quantity of organic waste digested: approx. 350,000 t. Expected to be 500,000 t in the future.
3) Gas yield: from slurry 22 m³/t, from waste 50 m³/t
4) $CO_2$ reduction due to displacement of fossil fuels: 2 kg $CO_2$/m³ biogas (see figure 25)
5) Reduced emissions of $CH_4$ and $N_2O$: approx. 26 kg $CO_2$-eqv./t, or 1.2 kg $CO_2$/m³ biogas. With improvements to housing and biogas technology, emission from particularly animal manure can be further reduced, maybe even halved.
6) Cutbacks in emissions in $CH_4$ and $N_2O$: estimated 200 kg $CO_2$-eqv./t, or 2 kg $CO_2$/m³ biogas.

# Nutrient utilisation and nutrient losses

No nutrients are lost in the biogas process as the gas produced mainly comprises $CH_4$ and $CO_2$. The same nutrient quantities that enter the plant in the original biomass can subsequently be found in the digested slurry. But the treatment and the process can still have a number of positive effects on the nutrient balances on the animal farms connected to the biogas plant. Figure 28 shows examples of the composition of different types of slurry.

## Phosphorus

Pig slurry typically has a higher content of phosphorus than what is needed for the optimal fertilisation of the crops in the rotation. This means that pig farms frequently overfertilise their crops. The reverse is true for cattle farms that often have to import extra phosphorus in mineral form.

In a biogas plant several different manures and biomasses are mixed and the nutrient concentration in the treated product returned to the farmer may not, therefore, be the same as in the untreated product delivered. Cattle slurry and organic waste often contain less phosphorus than pig slurry and the pig farmer will therefore usually get back less phosphorus than he delivered, while the cattle farmer will get more for the same amount of slurry (see figure 29).

In this way the nutrients are, to a certain extent, redistributed among the suppliers, which means that pig farmers reduce their overfertilisation with phosphorus somewhat and will need to buy less potassium, while cattle farmers can save on the phosphorus account but will have to purchase more potassium.

Animal farms in Denmark are, unfortunately, not evenly distributed over the country. Cattle farms are typically found in West Jutland and pig farms in East Jutland and on the islands. The redistribution is thus not always quite as optimal as it could be.

| | DM, % | Total N, kg/t | NH$_4$-N, kg/t | Phosphorus (P), kg/t | Potassium (K), kg/t | pH |
|---|---|---|---|---|---|---|
| Cattle slurry | 6.0 | 5.0 | 2.8 | 0.8 | 3.5 | 6.5 |
| Pig slurry | 4.0 | 5.0 | 3.8 | 1.0 | 2.0 | 7.0 |
| Digested slurry (mixed) | 2.8 | 5.0 | 4.0 | 0.9 | 2.75 | 7.5 |

Figure 28. Composition of different types of slurry. Typical nutrient contents in untreated slurry and digested slurry at an equal input of cattle and pig slurry.

| | Nutrient contents in digested slurry as a percentage of that in untreated slurry (equal inputs of cattle and pig slurry) | | | |
|---|---|---|---|---|
| | Nitrogen (N) | | Phosphorus (P) | Potassium (K) |
| | Total-N | NH$_4$-N | | |
| Cattle farm | 100 | 143 | 113 | 79 |
| Pig farm | 100 | 105 | 90 | 138 |

Figure 29. Percentage nutrient content in returned, digested slurry compared to the untreated slurry supplied.

## Nitrogen

As figures 28 and 29 show, something happens to nitrogen during the process. While the total amount of nitrogen is unaltered, the ratio between organic nitrogen and ammonium-N contents changes in favour of plant-available ammonium. The largest change is in cattle slurry, but is even larger in solid manures.

The change affects how well the nitrogen is utilised, because ammonium-N can be directly taken up by plants, while the organic compounds have to decompose first to release the N, which takes time. The fertiliser effect is, therefore, higher in treated slurry than in untreated slurry and the loss of nitrogen by way of leaching is, therefore, potentially also less.

On the other hand, the risk of ammonia volatilisation rises with increases in the ammonium-N content, and as digested slurry does not naturally form a surface crust in the storage tank, the risk of volatilisation during storage is heightened. The law stipulates, however, that slurry storage tanks must have a surface crust and so the farmer has to establish it himself. He can do this by using material such as chopped straw or Leca granules. This can reduce the volatilisation from around 20 to only a few percent of the nitrogen content of the stored slurry.

There is also an increased risk of ammonia volatilisation during slurry application, because of the higher ammonium-N content. But as treated slurry is much thinner than untreated slurry (as evidenced by the DM content in figure 28), the slurry percolates much faster into the soil, where the ammonia either dissolves in water or binds to particles. In practical terms, the level of volatilisation is therefore not larger from treated slurry

than from untreated slurry even when applied to the soil surface by trailing hoses.

Due to the higher nitrogen use efficiency of digested slurry, there is a considerable potential for reducing nitrogen losses by applying it to crops. The potential is illustrated in figure 30 below.

In reality, the relationships are much more complex than those outlined here. Different crops have, for example, different nitrogen norms (permitted amounts of nitrogen that can be applied) and the fertiliser used is often a mixture of slurry and mineral fertilisers that have different nitrogen use efficiencies. Some of the losses will be from organically bound nitrogen or from nitrogen built up in roots and then released in subsequent years. Climatic conditions also have an impact on the balance (precipitation and evaporation).

## ODOUR

As we all know, slurry has a pretty strong smell when it is applied to fields. The smell is due to not less than 300 different compounds that all contribute to the total odour profile. Some compounds have an extremely low odour detection threshold – that is, people can detect the compound at incredibly low concentrations, while other compounds have a much higher threshold.

A number of these compounds are broken down in the biogas process, but others are formed in their place. The number of odour units (OU) is therefore often just as high above a digested slurry as it is above an untreated slurry. There is, nevertheless, a marked difference when the slurry is applied. The odour is not as strong and pungent from digested slurry as from raw slurry,
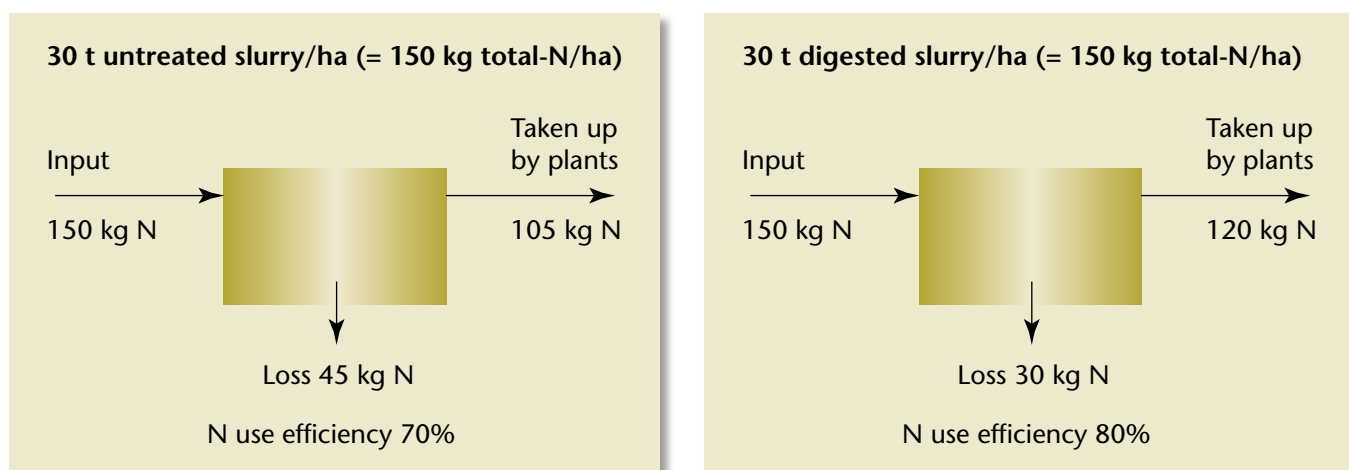


Figure 30. Simplified nitrogen balance when using untreated slurry (½ cattle, ½ pig) and digested slurry.

and it also disappears faster from a fertilised field, partly because the digested slurry percolates faster into the soil due to its lower DM content. Odour reduction during slurry application is also one of the main reasons why farmers decide to participate in biogas projects (see figure 31).

There can, on the other hand, be a higher potential risk of odour problems around the biogas plant itself. Large amounts of more or less foul-smelling biomasses are collected and treated here, and in the biomass reception area and reception tanks there will unavoidably be a considerable release of malodorous compounds. With a careful system of ventilation, extraction and subsequent air purification, it is possible to reduce this to an acceptable level. Nevertheless, protests from neighbours who fear there will be problems with odour are still the largest stumbling block to the establishment of new communal biogas plants. There is no doubt, however, that biogas plants generally reduce problems with odour caused by animal manure.

# DEGRADATION OF POLLUTANTS

Pollutants are found in many biomasses, including slurry and sludge, with detergents as one of their main sources. Some pollutants can have disruptive hormonal effects and are suspected of altering the gender of fish, among other things. Many are organic compounds and most of them are degraded in the anaerobic process. A few of them are, however, more biostable and are on the whole only degraded in an aerobic environment. The substances are often bonded to organic matter and the degradation is mainly biological. This means that the degradability usually increases with temperature. Finally, the molecular weight often plays a role where the degradability of the molecule is inversely related to its weight.

The degradability of pollutants has so far only been studied at few biogas plants, such as the one in Lemvig. The studies show that the degradation of pollutants is nearly 100% as no pollutants were found in significant concentrations in the digested slurry.

## Decontamination of slurry

Infectious agents, such as bacteria, vira and parasites that can cause disease in humans and animals, enter the biogas system via the animal manure and waste received at the plant.

The concentration of faecal streptococci (FS) that are in themselves harmless is always very high in untreated slurry and the FS number is an indirect indication of how many other potentially harmful bacteria, such as salmonella, may be present. Measurements from communal biogas plants show that streptococci may number up to 10 million/g in untreated slurry and be reduced to < 5/g (= 0) following digestion. The same is true for most other bacteria. The decontamination is thus very efficient and nearly absolute. Animal parasites are also virtually eliminated in the slurry in a traditional plant and experience shows that the health of the stock on a farm attached to a biogas plant is often better than normal.

Finally, the treatment of the slurry in the biogas plant ensures that weed seeds lose their ability to germinate. The result is that the weed pressure in the field is reduced and that the amount of herbicide used can be reduced.
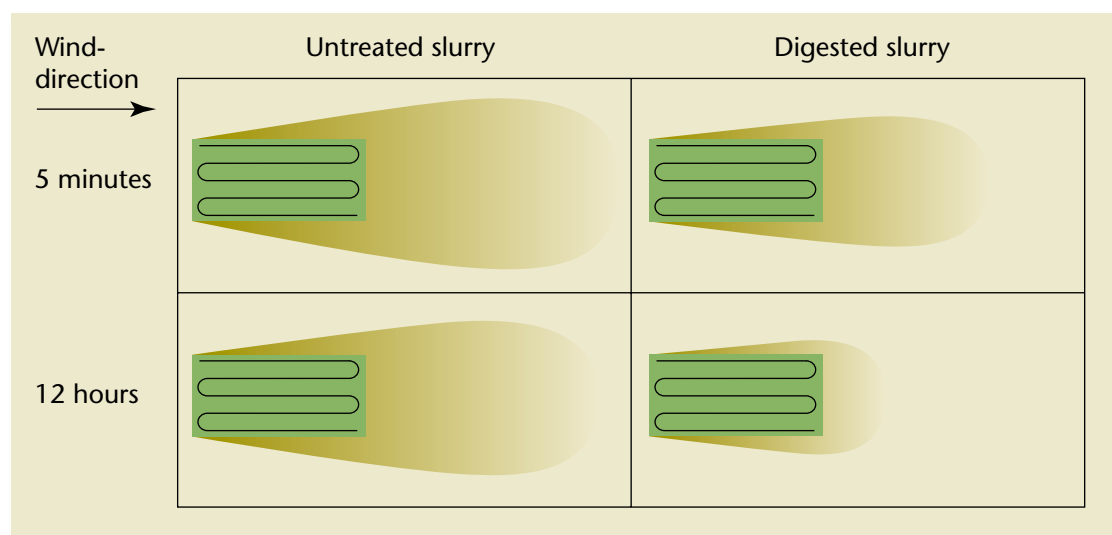


Figure 31. Odour dispersion at, respectively, five minutes and twelve hours after application of untreated and digested slurry.

# SEPARATION OF DIGESTED BIOMASS

Many people regard the separation of slurry – raw or digested – as a useful tool to solve the problems with overfertilisation and loss of nutrients to the environment in animal farming.

The theory is that by separating the nutrients – either wholly or in part – it becomes easier to export a surplus.

## Low-technology separation

With low-tech separation of digested slurry (using a decanter centrifuge, for example), dry matter and nutrients will typically be divided up as outlined in figure 32.

The fibre fraction contains most of the dry matter and is made up of undegradable organic substances (especially lignin), minerals, sand and bacterial cells. The fraction has a DM content of around 30%, the structure of a fine compost, and has to be applied with a manure spreader. It is very suitable as a soil conditioner as it contains substances that help in the build-up of humus in the soil. The concentration of phosphorus is high and the fraction is therefore suitable for fertilising phosphorus-deficient areas, but the nitrogen concentration is relatively low and as most of it is in the form of organic N it has a low fertiliser effect.

The fibre fraction is not stable but will, when stored, start composting spontaneously. Heat is produced in the heap and organic N becomes mineralised and some is lost by ammonia volatilisation. This puts special demands on the storage – and transport – of this fraction.

The liquid fraction consists mainly of wa-

| Digested biomass | kg | kg/t |
|---|---|---|
| Quantity | 1,000 | – |
| Dry matter, 2,8% | 28 | 28 |
| Water | 972 | 972 |
| Total-N | 5 | 5 |
| $NH_4$-N | 4 | 4 |
| Phosphorus, P | 0.9 | 0.9 |
| Potassium, K | 2.8 | 2.8 |

Separation

| Fibre fraction | kg | kg/t |
|---|---|---|
| Quantity | 80 | – |
| Dry matter, 30% | 24 | 300 |
| Water | 56 | 700 |
| Total-N | 1.25 | 15.6 |
| $NH_4$-N | 0.3 | 3.8 |
| Phosphorus, P | 0.7 | 8.8 |
| Potassium, K | 0.2 | 2.5 |

| Liquid fraction | kg | kg/t |
|---|---|---|
| Quantity | 920 | – |
| Dry matter, 0,4% | 4 | 4.3 |
| Water | 916 | 995 |
| Total-N | 3.75 | 4.1 |
| $NH_4$-N | 3.7 | 4.0 |
| Phosphorus, P | 0.2 | 0.2 |
| Potassium, K | 2.6 | 2.8 |

*Figure 32. Low-technology separation with a decanter centrifuge. The digested slurry is separated into two fractions. The fibre fraction contains approx. 30% dry matter, which is rich in organic matter and is a good soil conditioner. This fraction also contains most of the phosphorus. The liquid fraction only contains 0.4% dry matter, but most of the ammonium-N. The separation enables a more precise and efficient use of the slurry.*

ter and resembles very thin slurry. It contains most of the ammonium-N and is thus a fast-acting fertiliser that either has to be applied with trailing hoses or injected. Under favourable conditions, it is possible to achieve a nitrogen use efficiency that is just as high as with mineral fertiliser, i.e. 90-95%.

One of the advantages for the farmer with this system is that where he is normally only allowed to apply 140 kg N/ha with animal manure, he can apply up to the maximum quota if he uses the liquid fraction, which is 168 kg N/ha. With 4.1 kg N/t he can thus apply 40 t/ha, where he would normally only use 28 t/ha (5 kg N/t). This saves him some transport and maybe also some mineral fertiliser. Whether this is sufficient to offset the extra costs involved is, however, another question.

## High-technology separation

It is possible to further separate the liquid fraction to give a higher concentration of nutrients and there are several high-tech methods available for this.

One of the simple methods is evaporation where the water is heated and evaporated. If all the water is evaporated you end up with a syrupy mass that contains the remaining nutrients and minerals. The process requires acidification or other treatment of the liquid fraction in order to retain the ammonia. The advantage of this method is that you remove a lot of the water, which is expensive to transport. The drawback is that the process is very energy-demanding and the equipment obviously not free either.

Another method is to remove the nitrogen from the liquid. This can be done by what is called ammonia stripping. By adding an alkali, for example sodium hydroxide – NaOH, the equilibrium $NH_4^- \longleftrightarrow NH_3 + H^+$ is shifted to the right, and if the biomass is then heated, the ammonia evaporates with some of the water. The water/ammonia subsequently condenses and you get a watery solution with a high nitrogen content. The nitrogen will, however, be very volatile and will easily evaporate, which is why you have to acidify the solution by adding an acid.

The process is relatively complicated and thus also rather costly, and you are left with a liquid fraction that contains nearly all the potassium. This fraction can be applied with an irrigation system. But if the potassium has to be used optimally, you cannot apply it all on a limited area, although you are allowed to apply several years of potassium fertiliser in one go. This, of course, gives a saving on transport.

Alternatively, you can extract the potassium from the liquid using membrane filtration techniques, or similar techniques.

As the above implies, a separation of slurry and digested slurry is quite expensive, certainly when using high-tech methods. Before opting for any one of the methods, you therefore have to carefully consider what the purpose is and not least the cost. The costs of using a low-tech separation method alone, which always precedes a high-tech one, are approx. 20 kr./t (10 kr./t operating costs and 10 kr./t in interest and repayments on a loan to buy the equipment). That is also approximately what it costs to transport slurry with a slurry tanker a reasonable distance, say 10-15 km. In order for separation to be profitable, the distance that the fertiliser material has to be transported therefore needs to be fairly large.

# INDEX